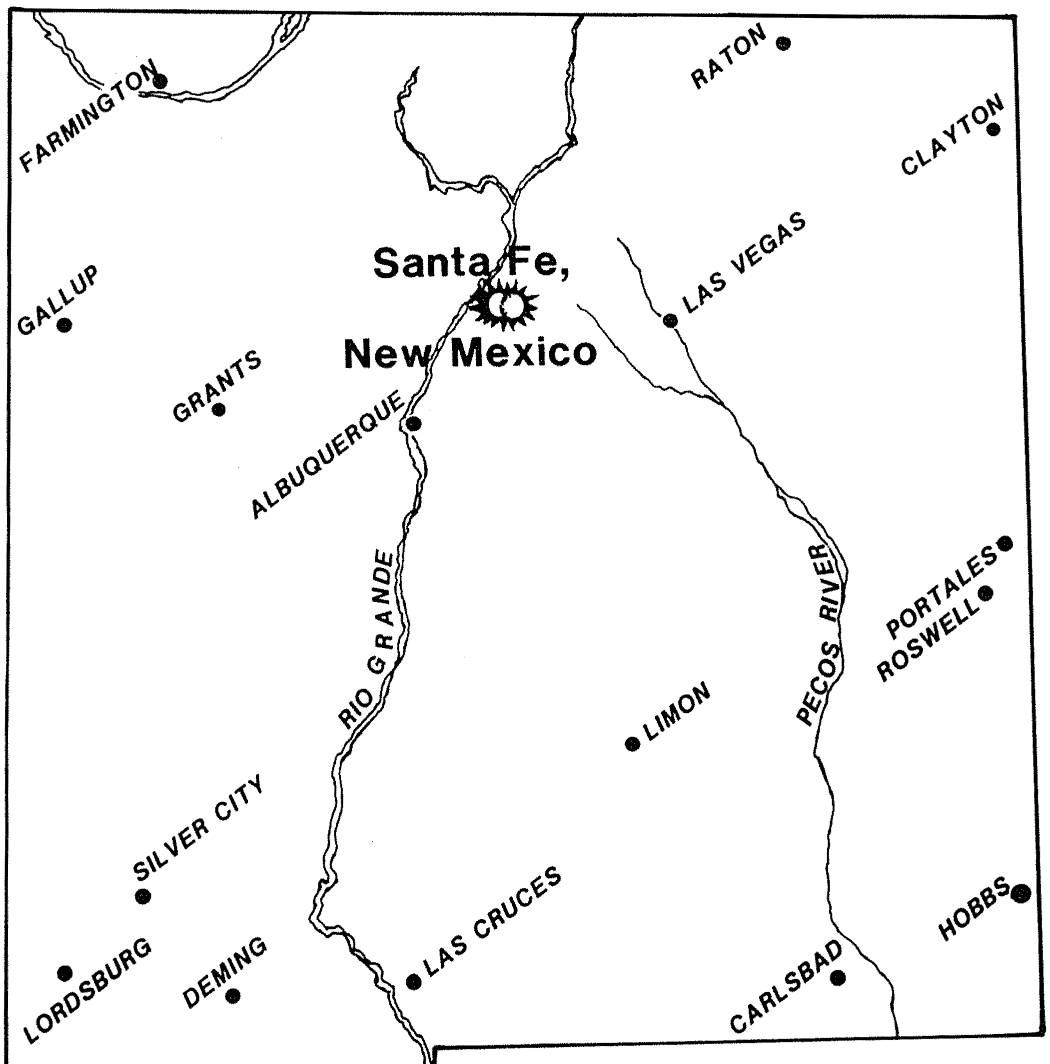
MINER

Annual Sherwood CONTROLLED FUSION THEORY Conference



April 25 - 28, 1982
Santa Fe, New Mexico

HOSTED BY:

Los Alamos

Los Alamos National Laboratory/Operated by University of California

ANNUAL CONTROLLED FUSION

THEORY CONFERENCE

April 25-28, 1982

Santa Fe, New Mexico

Sponsored by

Los Alamos National Laboratory

Los Alamos, New Mexico 87545

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R.L. Morse	G. Smith	
T.N. Oneil	R. Waltz	
W.L. Sadowski		
D.D. Schnack		
D.J. Sigmar		
R.B. White		

SCHEDULE

Sunday, April 25, 1982

6:00 - 10:00 p.m.	Registration
8:00 - 10:00	Reception (music, food, cash bar)

Monday, April 26, 1982

8:15 - 8:30	Welcome
8:30 - 10:00	Oral Session 1A
10:00 - 10:30	Coffee Break
10:30 - 12:30	Oral Session 1B
12:30 - 2:00	Lunch
2:00 - 3:30	Poster Session 1C
3:00 - 4:00	Break
4:00 - 5:30	Poster Session 1D
7:30 - 9:00	Poster Session 1E

Tuesday, April 27, 1982

8:00 - 9:20	Review Paper Session 2A
9:20 - 10:20	Oral Session 2B
10:20 - 10:45	Coffee Break
10:45 - 12:15	Oral Session 2C
12:15 - 7:00	Open Time
7:00 - 8:30	Poster Session 2D
8:30 - 9:00	Break
9:00 - 10:30	Poster Session 2E

Wednesday, April 28, 1982

8:00 - 10:00	Oral Session 3A
10:30 - 11:00	Coffee Break
11:00 - 12:00	Oral Session 3B
12:00 - 1:00	Lunch
1:00 - 2:30	Poster Session 3C

*** ALL POSTER SESSIONS WILL BE HELD IN NEW MEXICO ROOM AT LA FONDA ***

*** ALL ORAL SESSIONS WILL BE HELD IN THE HILTON HOTEL BALLROOM ***

GENERAL INFORMATION

All Oral sessions will be held in the Hilton Ball Room.

All Poster sessions will be held at the La Fonda in the New Mexico Room. There will be three poster session on Monday. There will be only one poster session on Wednesday afternoon. Each session will last 1 1/2 hours with a thirty minute break in between.

Registration will take place at the Hilton Hotel from 6:00 p.m. to 10:00 on Sunday, April 25. In conjunction with the Sunday registration there will be a reception party from 8 to 10 in the Hilton Ball Room. Musical entertainment, food and punch will be provided. A cash bar will also be available.

Assistance will be available for travel thru Santa Fe World Travel Agency. The phone number is 988-4463. There is a service charge for flight changes $10 for domestic and $20 for foreign flights. All other problems will be handled at the registration desk throughout the conference.

There have been 281 papers submitted, of which 18 were selected for oral presentation. Those giving talks may, at their option, present posters the afternoon following their talk.

1982 SHERWOOD MEETING
THEORETICAL ASPECTS OF CONTROLLED THERMONUCLEAR RESEARCH
April 25,28,1982 Santa Fe Hilton Santa Fe,New Mexico

SUNDAY APRIL 25

6:00-10:00pm REGISTRATION HILTON HOTEL
8:00-10:00 REGISTRATION AND RECEPTION HILTON BALLROOM

MONDAY, APRIL 26

7:30 - 5:00 REGISTRATION HILTON HOTEL
(ASSISTANCE AVAILABLE THROUGHOUT CONFERENCE)

8:15 - 8:30 WELCOME HILTON BALLROOM
CHAIRMEN - ED CARAMANA

8:30 - 10:00 ORAL SESSION 1A HILTON BALLROOM

8:1. Resistive Stability in Cylindrical Geometry; Spheromak Applications. S. C. Jardin, J. DeLucia, A. H. Glasser, R. C. Grimm, D. Hewett, C. Ryu, and G. Tesauro.
8:2. Global, Nonlinear Magnetic Reconnection in the Reversed Field Pinch. R. A. Nebel, E. Caramana, and D. D. Schnack.
8:3. Equilibrium and Stability of Elongated Field Reversed Configurations. R. L. Spencer, D. Hewett, J. L. Schwarzmeier, D. C. Barnes, and C. Seyler.

10:00 - 10:30 COFFEE BREAK

10:30 - 12:30 ORAL SESSION 1B

10:1. Drift Orbit in Toridal System with Imperfect Magnetic Surfaces. R. B. White and A. H. Boozer.
10:2. Toroidal Stellarator Fields with Nested Magnetic Surfaces. J. R. Cary.
10:3. Neoclassical Transport Equations Including Flows and Bootstrap Current In Nonaxisymmetric Toroids. J. D. Callen and K. C. Shaing.
10:4. Locally Coupled Evolution of Wave and Particle Distributions in General Magnetoplasma Geometry. A. N. Kaufman, C. Grebogi, and S. W. McDonald.

12:30 - 2:00 LUNCH

2:00-3:30 POSTER SESSION 1C (NEW MEXICO ROOM, LA FONDA)

2:1. Alpha Particle Driven Compressional Alfven Wave Instability in a Tandem Mirror Reactor. J. D. Hanson and E. Ott.
2:2. Enhancement in the Ion Thermal Conductivity in Neutral Beam Heated Tokamaks. C. S. Chang.
2:3. Time Evolution of the FRC: Spinup Through Distruption. D. S. Harned and D. Hewett.
2:4. Drift Wave Turbulence in a Low Order k Space. W. Horton, Jr. and P. Terry.
2:5. Strange Attractors in Crisis. C. Grebogi, E. Ott, and J. A. Yorke.
2:6. High Beta Tandem Mirror Equilibria in the Paraxial Limit. T. B. Kaiser, B. McNamara, L. D. Pearlstein, and P. Willman.
2:7. Electron Thermal Transport in Plasmas with Auxiliary Heating. P. T. Bonoli, R. Englade, and B. Coppi.
2:8. Low m Number Stability of the Elmo Bumpy Torus. K. D. Cogswell and J. P. Freidberg.
2:9. High Frequency Instabilities in Hot Electron Plasmas. Y. Chen, W. M. Nevins, and G. R. Smith.
2:10. Theory and Simulation of Microinstabilities in Field Reversed Configurations. N. T. Gladd, A. G. Sgro, C. Lilliequist, and D. Hewett.
2:11. Non Linear Evolution of 2D Lower Hybrid Drift Wave Turbulence. J. D. Huba, J. F. Drake, and P. N. Guzdar.
2:12. Rotational Stability of Tandem Mirrors. D. A. D'Ippolito and J. P. Freidberg.
2:13. MHD Analysis of PDX Discharges. R. Izzo, W. Park, D. A. Monticello, K. McGuire, D. Buchenauer, and H. R. Strauss.
2:14. Nonresonant Electron Transport in EBT. D. E. Hastings and D. A. Spong.
2:15. Time Acceleration of Transport Equations for Generating Steady State Solutions. W. A. Houlberg and S. E. Attenberger.
2:16. Ambipolarity of High Energy Collisionless Ions in EBT. E. F. Jaeger, D. E. Hastings, J. S. Tolliver, and C. L. Hedrick.
2:17. EBT Transport and Orbits for Pedestrians. C. L. Hedrick, D. E. Hastings, E. F. Jaeger, and J. S. Tolliver.
2:18. Theory of Two Point Correlation for Trapped Electrons and the Frequency Spectrum of Drift Wave Turbulence in Tokamaks. P. H. Diamond and P. Terry.
2:19. Speed: A Code for Calculating Scalar Pressure Equilibria in the EBT Device. W. H. Miner, A. Kadish, and H. Grad.
2:20. The Whistler Instability Driven by Relativistic Lost Cone Electron. K. T. Tsang.
2:21. Dynamic Coupling of the Plasma, Shell, Coils, and Iron in ZT-40M. R. W. Moses.
2:22. Current Gradient Driven Low Frequency Electrostatic Modes. R. Farengo, Y. C. Lee, and P. N. Guzdar.
2:23. Kinetic Theory of Stability in EBT with Hot Electron Annulus. S. Z. Zhao and Y. P. Pao.
2:24. Universal Mode Stability from the Theory of the Two-Point Correlation. P. Terry and P. H. Diamond.
2:25. High Beta Stability of Ideal MHD Fixed Boundary Modes. G. B. Crew and J. J. Ramos.
2:26. Formation Studies of Field Reversed Configurations: Spontaneous B Toroidal?. D. Hewett.
2:27. Numerical Calculation of ICRF Fields in EBT Devices. C. W. Nestor, D. B. Batchelor, and H. Weitzner.
2:28. Transport Minimizing Equilibria for Tandem Mirrors. J. R. Myra, D. A. D'Ippolito, and P. J. Catto.
2:29. Modeling of the ZT-40 RFP Experiment. K. A. Werley and G. H. Miley.
2:30. Large Scale Particle Simulations in a Virtual Memory Computer. P. C. Gray, J. S. Wagner, and T. Tajima.

2:31. Do Distortions of the Bulk Ions from Maxwellians Affect Fusion Reactivity in TFTR?. A. A. Mirin and G. P. Tomaschke.
2:32. Calculation of Self Consistent Radial Electric Fields in Tandem Mirrors. S. P. Auerbach, R. H. Cohen, J. M. Gilmore, A. A. Mirin, L. D. Pearlstein, and M. E. Rensink.
2:33. Numerical Simulation of the Bootstrap Current. J. L. Shohet.
2:34. Equilibrium and Stability of Configurations with Spatial Magnetic Axis. H. Weitzner and M. Mond.
2:35. Resonant Ion Transport in EBT. J. S. Tolliver, D. E. Hastings, E. F. Jaeger, and C. L. Hedrick.
2:36. Model Equations for Coupled Drift and Shear Alfven Turbulence. P. K. Kaw.
2:37. Anomalous Fast Ion Due to Magnetic Field Fluctuations. R. W. Harvey, D. K. Bhadra, T. Yamagishi, and R. L. Miller.
2:38. Current Driven Resistive MHD Instabilities in Axisymmetric Toroidal Systems. J. Manickam, R. C. Grimm, and R. L. Dewar.
2:39. Analytical and Numerical Calculations of Nonadiabaticity in EBT Geometry. S. Hamasaki, N. A. Krall, and J. L. Sperling.
2:40. Calculation of Stellarator Currents at Low Collisionality. H. E. Mynick.
2:41. Ion Heating By RF Waves in a Bumpy Torus. J. L. Sperling, S. Hamasaki, and N. A. Krall.
2:42. Conditions for the Attainment of the Minimum Energy State of a Diffuse Pinch Discharge. M. G. Rusbridge.
2:43. Two Dimensional Solitary Drift Wave with Magnetic Shear and Electron Kinetics. J. D. Meiss and W. Horton, Jr..
2:44. Numerical Simulation on Electron Cyclotron Resonance Heating. H. Okuda and H. Abe.

3:00 - 4:00 REFRESHMENTS

4:00 - 5:30 POSTER SESSION 1D

4:1. MHD Stability Limit and Growth Rates in Straight Stellarators with Strong Shear. P. Merkel, J. Nuhrenberg, W. Schneider, R. Gruber, and F. Troyon.
4:2. Three Dimensional MHD Particle Code for High Beta Tokamak Simulation. F. Brunel and T. Tajima.
4:3. Instabilities Driven by the Parallel Variation of the Electrostatic Potential in Tandems. R. E. Aamodt, X. S. Lee, and P. J. Catto.
4:4. Simulation of Current Drive with Lower Hybrid Waves. V. K. Decyk, J. M. Dawson, and G. Morales.
4:5. Simulation of Iron Transport in Counter Injected ISX-B Plasmas. C. Crume and D. E. Arnurius.
4:6. Beam and Alpha Particle Effects on Tokamak Microinstabilities. G. Rewoldt and W. M. Tang.
4:7. Simulations of the Toroidal Cusp Experiment. J. M. Dawson, J. N. Leboeuf, N. C. Luhmann, Jr., S. T. Ratliff, and M. Rhodes.
4:8. Stability of Multihelical Tearing Modes in Shaped Tokamaks. W. Kerner and H. Tasso.
4:9. Electron Transport in Stellarators. R. M. Kulsrud and D. Ho.
4:10. Pressure Gradient Driven Toroidal Drift Modes. W. C. Anderson and W. Horton, Jr..
4:11. The Importance of Poloidal Non Linear and Finite Ion Poloidal Gyro Radius in Tokamaks Impurity Transport. A. A. Ware.
4:12. Transport Coefficients in Weakly Turbulent Plasmas. G. Hazak and I. B. Bernstein.
4:13. How Flux Surfaces Break Up. R. S. Mackay.
4:14. Stability of High Beta Tokamak Spectral Equilibria. K. M. Ling, S. C. Jardin, and D. A. Monticello.
4:15. Time Varying Magnetic Pumping in Tandem Mirrors. J. A. Byers, R. H. Cohen, D. E. Baldwin, and P. Poulsen.
4:16. Numerical Studies of Large k Ballooning Modes in Helical Equilibria. R. Gruber, F. Troyon, P. Merkel, J. Nuhrenberg, and W. Schneider.
4:17. Effect of ICRF on the Ion Tail Distribution. S. C. Chiu and C. S. Liu.

4:18. Collisionless Diffusion in Two Frequency ECRH. J. E. Howard, A. J. Lichtenberg, M. A. Lieberman, and R. H. Cohen.
4:19. Evaluation of the MHD Continuous Spectrum. M. S. Chance, J. M. Greene, and H. Selberg.
4:20. Simulations of Upper Hybrid and Electron Cyclotron Heating. A. T. Lin and C. C. Lin.
4:21. A Theory of the Relaxation of Finite Beta Toroidal Plasmas. J. E. Brandenburg.
4:22. Character of Ion Orbits in an Elliptical Z Pinch. J. S. Kim and J. R. Cary.
4:23. Theory of Electron Beam Injected Mirror Plasma. A. Avinash and R. K. Varma.
4:24. Non Linear Theory of Finite Beta Drift Wave Turbulence. C. Beasley, J. P. Freidberg, K. Molvig, and W. Van Rij.
4:25. Linear Oscillations in General Magnetically Confined Plasmas. L. Chen and S. T. Tsai.
4:26. Drift-Ideal Magnetohydrodynamics. A. B. Hassam and Y. C. Lee.
4:27. Effects of Magnetically Confined Electrons on Potential Formation in Tandem Mirror Thermal Barrier. R. H. Cohen.
4:28. Magnetic Field Lines and Particle Orbits in Toroidal Plasma Equilibria. M. A. Marcel.
4:29. Nonlinear Interaction of Drift Tearing Modes of Different Helicities. H. R. Hicks, B. A. Carreras, J. A. Holmes, and B. F. Masden.
4:30. Relativistic Broadening Near Cyclotron Resonance. K. Imre and H. Weitzner.
4:31. Nonadiabatic Particle Motion in EBT. G. L. Chen, D. B. Batchelor, C. L. Hedrick, and L. W. Owen.
4:32. Theory of Current Penetration in the Pretext Tokamak. J. C. Wiley, A. Y. Aydemir, A. Bhattacharjee, R. D. Hazeltine, and S. M. Mahajan.
4:33. Equilibria in Axisymmetric Tandem Mirror Configuration. N. S. Kim, R. W. Conn, and L. L. Lao.
4:34. Analytical Representation of Ion Confinement in Tandem Mirror Plugs. D. L. Glabraith and T. Kammash.
4:35. Correlation Decay of Periodic, Area-Preserving Maps. J. D. Crawford, A. N. Kaufman, H. D. Abarbanel, C. Grebogi, J. D. Meiss, and J. R. Cary.
4:36. Radial Transport in Non-Symmetric Geometries: Explicit Upper Bound Expressions and Application to Tandem Mirror. K. Hizandis, K. Molvig, R. H. Cohen, and I. B. Bernstein.
4:37. Driven Magnetic Reconnection Processes. B. Coppi.
4:38. A Variational Principle for Plasmas Confined by Nonsymmetric Magnetic Fields. S. P. Hirshman.
4:39. Kinetic Ballooning Modes in Quadrupole Stabilized Tandem Mirrors. W. M. Nevins and L. D. Pearlstein.
4:40. Considerations of Stability Limits in Future EBT Devices. N. A. Uckan and D. A. Spong.
4:41. Electron Thermal Conductivity in Tokamaks. T. Yamagishi, C. S. Chang, D. K. Bhadra, and C. S. Liu.
4:42. Simulation Studies of Effects of Hot Electron Ring on Flute Instabilities for an EBT Like Geometry. Y. Ohsawa and J. M. Dawson.
4:43. Linear Theory of Electromagnetic Stability in a Parabolic Q-Profile. R. D. Hazeltine and S. M. Mahajan.
4:44. Weak Turbulence Theory of Ballooning Modes. R. W. Moore, D. K. Bhadra, R. R. Dominguez, and C. S. Liu.

7:30 - 9:00 POSTER SESSION 1E

7:1. Spectrum of Drift Wave Turbulence in a Sheared Magnetic Field. A. K. Sen, S. Kim, and T. Tange.
7:2. Magnetic Reconnection Driven by the Coalescence Instability. A. Bhattacharjee, F. Brunel, and T. Tajima.
7:3. Determination of the Perturbed Density Distribution Function for a Semi Infinite Plasma. M. R. Sands and B. D. Ganapol.
7:4. Excitation of Global Eigenmodes Associated with Alfven Discrete Spectrum. K. Appert, R. Gruber, F. Troyon, and J. Vaclavik.

7:5. Heating and Superadiabaticity for Single and Multiple Frequency ECRH. T. D. Rognlien.
7:6. Oxygen Contamination Diagnosed with Three VUV Spectral Lines. C. Lilliequist, A. G. Sgro, E. Caramana, N. H. Magee, J. Abdallah, A. L .Merts, and C. Crume.
7:7. Toroidal RFP Equilibrium and Stability Against Ideal and Resistive Localized Modes. R. Y. Dagazian and M. S. Chance.
7:8. An Analytical Solution to a Model Fokker Planck Equation. E. B. Parlette and B. D. Ganapol.
7:9. Renormalized Particle Codes and Their Applications. J. N. Leboeuf and T. Tajima.
7:10. Stabilization of the Internal Kink Mode in Finite Beta Toroidal Plasmas. J. J. Ramos and G. B. Crew.
7:11. SAYTR2: A D-D Fueled Tandem Mirror Reactor. D. C. Baxter, D. Dobrott, and G. W. Shuy.
7:12. SPECTR3: A 3D MHD Code for the RFP. D. D. Schnack and E. Caramana.
7:13. Computer Simulations of Ion Cyclotron Resonance Heating in Tokamaks. M. Makino, J. N. Leboeuf, T. Tajima, and K. Whang.
7:14. Particle Like Nature of Zero Frequency Waves. C. Chu.
7:15. Finite Larmor Radius Effects on Curvature Driven Instabilities in Hot Electron Plasmas. J. W. VanDam, H. L. Berk, C. Z. Cheng, and M. N. Rosenbluth.
7:16. MHD Ballooning Modes in EBT. Y. P. Pao.
7:17. Guiding Center Plasma Simulations. A. Y. Aydemir, D. C. Barnes, and T. Kamimura.
7:18. 3D MHD Equilibrium Calculation of the Cleftron. T. S. Wang and T. Ohkawa.
7:19. Solitons Generated by Boundary Motion. C. K. Chu and L. W. Xiang.
7:20. Stability of Relaxed Spheromak Equilibria. G. Marklin and A. Bondeson.
7:21. Quasistatic Evolution of Compact Toroids. A. G. Sgro, R. L. Spencer, and C. Lilliequist.
7:22. Sloshing Ion Distributions in MFTF-B. M. E. Rensink.
7:23. Free Boundary Stability of a Finite Beta, l=1 Stellarator. D. C. Barnes and J. R. Cary.
7:24. More Accurate Plasma Equilibria for Compact Tori and Axisymmetric Tandems. B. McNamara and D. M. Whitney.
7:25. Can Stable, Linear Resistive Modes Give Dynamo Action?. T. Hewitt, R. Keinigs, R. A. Nebel, and R. A. Gerwin.
7:26. Alfven Resonance Heating of Spheromaks. S. Riyopoulos and E. Ott.
7:27. Stochastic E x B Particle Motion Due to Two Electrostatic Waves. R. G. Kleva and J. F. Drake.
7:28. Some Effects of Hot Electron Stability in Tandem Mirror Geometry. D. E. Baldwin.
7:29. Nonlinear Pressure Driven Modes and Possible Relationships to Energy Containment in the RFP. T. C. Hender and D. C. Robinson.
7:30. MHD Turbulence in Tokamak Plasmas. D. Biskamp and H. Welter.
7:31. Application of Stellarator Expansion Techniques to Tokatron Configurations. J. L. Johnson and G. Anania.
7:32. Electromagnetic Wave Generation in a Beam Plasma System. P. L. Pritchett and J. M. Dawson.
7:33. Diffusion of Fusion Produced Particles Due to Shear Alfven Fluctuations. F. Pegoraro, L. Sugiyama, and S. Normale.
7:34. Nonlinear Gyrokinetic Equations for Low Frequency Electromagnetic Waves in General Plasma Equilibria. E. A. Frieman and L. Chen.
7:35. Transport Coefficients of Trace Heavy Impurity Ions in a Rotating Plasma. S. K. Wong, M. Rosenberg, and K. H. Burrell.
7:36. Multi Region Bounce Averaged Fokker Planck Code and Study of Thermal Barrier in a Tandem Mirror. Y. Matsuda and J. J. Stewart.
7:37. Generation of Hybrid Field Reversed Equilitoria. E. C. Morse and Z. Mikic.
7:38. Particle Transport in Reversed Field Pinches. C. Seyler.
7:39. Low Q Limiter Discharges and Kink Instability. L. C. Bernard, F. J. Helton, J. K. Lee, and R. W. Moore.
7:40. A Data File of Iron Ion Excitation Collision Strengths. J. B. Mann.
7:41. A Linear Model for the Tearing Mode of a Tokamak Plasma with Flow and a "Resistive Wall" Boundary Condition. T. H. Jensen.
7:42. "Ensemble Modes" in the Nonadiabatic Behaviour of Particles in Inhomogeneous Magnetic Fields. R. K. Varma.

7:43. Stability Studies Using the Stellarator Expansion. G. Anania and J. L. Johnson.
7:44. A Class of Toroidal Stellarator Equilibria. J. P. Freidberg and P. Rosenau.

TUESDAY, APRIL 27

8:30 - 9:20 ORAL SESSION 2A (HILTON BALL ROOM)
CHAIRMAN - JEFF FRIEDBERG

REVIEW PAPER - ROBERT KRAICHNAN

9:20 - 10:20 ORAL SESSION 2B

9:1. On the Relation Between "Mixing Length" and "Direct Interaction Approximation" Theories of Turbulence. R. N. Sudan and D. Pfirsch.
9:2. Numerical Study of Drift Wave Turbulence with Simple Models for Nonlinear Wave-Wave Coupling. R. E. Waltz.

10:20 - 10:45 COFFEE BREAK

10:45 - 12:15 ORAL SESSION 2C

10:1. Resistive Pressure Driven Modes in High Beta Tokamaks. B. A. Carreras, J. A. Holmes, W. A. Cooper, H. R. Hicks, V. E. Lynch, P. H. Diamond, and P. L. Similon.
10:2. MHD Fluctuations of Compressible Plasmas. H. A. Rose, E. Hameiri, and K. Riedel.
10:3. Tearing Modes in Toroidal Geometry. J. F. Drake, T. M. Antonsen, and Y. C. Lee.

12:15 LUNCH (free afternoon)

7:00 - 8:30 POSTER SESSION 2D (NEW MEXICO ROOM)

7:1. Unstable Continua in Ideal MHD. R. L. Dewar.
7:2. Equilbrium Studies for ATF-1 Configurations. L. Garcia, B. A. Carreras, J. H. Harris, and V. E. Lynch.
7:3. A Proposed Beta Limit Test Using Shape Control. R. L. Miller.
7:4. Ballooning Modes and the Continuous Spectrum in MHD. E. Hameiri and P. Laurence.
7:5. A Study of Lower Hybrid Ray Bundles with LHTOR. A. H. Glasser and G. J. Kuperberg.
7:6. MHD Equilibrium with Non Ideal Boundary Conditions. D. Montgomery, G. Vahala, and L. Vahala.
7:7. Slowing Down of Ion Rings. C. B. Ruchti and R. V. Lovelace.

7:8. Bounce Averaged Fokker Planck Quasilinear Diffusion Calculations in Toroidal Devices. G. Kerbel and M. G. McCoy.
7:9. Relativistic Effects on the Whistler Mode in EBT. P. N. Guzdar.
7:10. Minimum Energy States with Finite Pressure in Current Carrying Plasmas. J. Y. Hsu and J. K. Lee.
7:11. Kinetic Stability of Reversed Field Pinches. J. P. Mondt and T. Hewitt.
7:12. Reconnection Problem on Two Time Scales. P. N. Hu.
7:13. Decay Instability of Kinetic Alfven Wave in an Inhomogeneous Plasma. D. W. Ross, A. Sen, and A. K. Sundaram.
7:14. Effects of Sawteeth on Impurity Transport and Radiation Losses. F. H. Seguin and R. Petrasso.
7:15. Generation of Suprathermal Ions in Magnetic Traps. B. Hafizi and R. E. Aamodt.
7:16. Field Swelling Instability in Anisotropic Plasmas. B. Basu and B. Coppi.
7:17. Exploration of Bifurcated, High Beta Equilibria. D. J. Elkins and S. Johnston.
7:18. Trapping Current in the Thermal Barrier Region of a Tandem Mirror Machine. R. Carrera and J. D. Callen.
7:19. Three Dimensional "Imcompressible" Plasma Evolution. M. S. Chu.
7:20. Suppression of Magnetic Islands by RF Driven Currents. A. Reiman.
7:21. 3-D MHD Studies of High Beta Tokamak Discharges. W. Park, R. Izzo, D. A. Monticello, and R. B. White.
7:22. Magnetic Turbulence, Ergodicity and Anomalous Thermal Conduction in Tokamaks. F. A. Haas and A. Thyagaraja.
7:23. Number of Spatial Fourier Modes Controlling Navier Stokes Flows. Y. M. Treve.
7:24. Ambipolar Diffusion in Quasilinear Theory. H. L. Berk and K. Molvig.
7:25. Gyrokinetic Particle Simulation of Drift Wave Turbulence. W. W. Lee, L. Chen, C. Z. Cheng, and W. M. Tang.
7:26. Diffusion in ZT-40M Using a 1-D Radial Transport Code. R. B. Howell.
7:27. BGK Solutions to the Free Electron Laser Instability. B. Lane and R. C. Davidson.
7:28. Parametric Instabilities During Electron Cyclotron Resonance Heating of Tandem Mirrors. D. R. Nicholson.
7:29. Anisotropy Driven Compressional Alfven Effects in a Hot Electron Plasma. X. S. Lee, K. T. Tsang, and P. J. Catto.
7:30. Current Drive by LH Waves in the Presence of a DC Electric Field. V. Krapchev.
7:31. Kinetic Ballooning Modes in Tokamaks. R. R. Dominguez, R. W. Moore, and C. S. Liu.
7:32. Stability of Ballooning Modes in the Elmo Bumpy Torus (EBT). K. Nguyen and T. Kammash.
7:33. D-D Tokamak Reactor Assessment. D. C. Baxter, R. N. Byrne, A. E. Dabiri, D. Dobrott, J. E. Glancy, W. K. Hagan, J. B. McBride, and S. Tamor.
7:34. Formation, Equilibrium and Stability Considerations for Accelerated Compact Toroids. J. H. Hammer and C. W. Hartman.
7:35. Magnetic Perturbations in Tokamaks. R. N. Morris and G. Bateman.
7:36. Nonlinear Damping of Ion Cyclotron Waves and Harmonic Generation. C. F. F. Karney and A. Fukuyama.
7:37. A Multi-Dimensional, Selfconsistent, Kinetic Numerical Transport Method for Treating Chemistry Dominated Edge Plasmas. D. Morrison, R. Morse, and G. Sowers.
7:38. Anisotropy Effects on Microwave Absorption by Relativistic Electron Rings in EBT Devices. D. B. Batchelor, R. C. Goldfinger, and S. Tamor.
7:39. Intermediate Mode Number Ballooning Stability of Stellarator Tokamak Hybrids. W. A. Cooper and B. A. Carreras.
7:40. Structure of Wall Plasmas Near Divertor Neutralizer Plates or Limiters. P. Gierszewski, P. McKenty, J. McCullen, and R. Morse.
7:41. Ion Loss Cone Instabilities in Realistic 3-D Geometries. M. J. Grever.
7:42. Overstable Resistive Instabilities in the Diffuse Linear Pinch. C. Ryu and R. C. Grimm.
7:43. A Hybrid Language for Large Codes. O. Buneman.
7:44. A Theory of Macroscopic Invariants. L. S. Hall.

8:30 - 9:00 REFRESHMENTS

9:00 - 10:30 POSTER SESSION 2E

9:1. Nonlinear Evolution of the Resistive Interchange Mode in the Cylindrical Spheromak. J. DeLucia and S. C. Jardin.
9:2. Predictive Power of Perturbation Theory in Calculating the Effect of Localized RF Field Near the Gyrofrequency. B. M. Lamb, G. Morales, and G. Dimonte.
9:3. A One Dimensional Code for Field Reversed Mirror Dynamics. R. A. Stark and G. H. Miley.
9:4. Energy Redistribution in Igniting Plasmas. L. Sugiyama and R. Englade.
9:5. A Computational Model for Lower Hybrid Heating and Current Drive in Tokamaks. R. Englade and P. T. Bonoli.
9:6. A Sufficient Condition for Stability of Axisymmetric Collisionless Systems. A. E. Walstead.
9:7. Torodial Momentum Dissipation in Beam Injected Plasmas. J. Hogan.
9:8. Neutral Beam Injection and Plasma Instabilities Due to Anistropy. D. K. Bhadra, S. C. Chiu, and R. W. Harvey.
9:9. Study of Lower Hybrid Ion Heating With/Without Neutral Beam Injection. M. Rosenberg, S. C. Chiu, and C. S. Liu.
9:10. Theory and Simulation of Quasioptical Gyrotrons and Klystrogyrotrons. A. Bondeson, B. Levush, W. M. Manheimer, and E. Ott.
9:11. Ion Cyclotron Resonance Heating in a Strongly Inhomogeneous Magnetic Field. B. D. Fried, K. Nozaki, G. Morales, and A. Fukuyama.
9:12. A 3 D Model for Computing Self Consistent Transport Dominated Tandem Mirror Equilibria. D. V. Anderson.
9:13. Transport in Tokamak Plasmas with Arbitrary Toroidal Rotation. F. L. Hinton, S. K. Wong, and K. H. Burrell.
9:14. Non Linear Interaction of Toroidicity Induced Drift Modes. P. L. Similon and P. H. Diamond.
9:15. Nonlinear Evolution of a Single Tearing Mode Island. K. Swartz and R. D. Hazeltine.
9:16. The Dynamo Effect in the Reversed Field Pinch. R. Keinigs and R. A. Gerwin.
9:17. Correlation Functions for Noisy Nonlinear Maps. J. C. Whitson and S. P. Hirshman.
9:18. Transport, End Loss, and Ambipolarity in Tandem Mirrors. P. J. Catto and J. R. Myra.
9:19. Calculation of Island Size Driven by an External Source. J. K. Lee, H. Ikezi, T. H. Jensen, and N. Ohyabu.
9:20. Stabilization of Tandem Mirror Trapped Particle Modes by Incomplete Cancellation of Particle Drifts. L. D. Pearlstein, D. E. Baldwin, R. H. Cohen, T. K. Fowler, and B. G. Logan.
9:21. Second Order Hamiltonian for Guiding Center Particle Motion. D. C. Stevens and H. Weitzner.
9:22. Antenna Plasma Coupling Theory for ICRF Heating. A. Ram and A. Bers.
9:23. Stability of Compact Torus - Ion Ring Hybrid System to Non Axisymmetric Modes. A. D. Turnbull and R. N. Sudan.
9:24. Restricted Multiple Three Wave Interactions. C. R. Menyuk, H. H. Chen, and Y. C. Lee.
9:25. Hamiltonian Formulation of Field Line Flow. R. G. Littlejohn and J. R. Cary.
9:26. A Comparison of Small vs. Large Angle Scattering in Magnetized Plasmas. A. Andrade, T. A. Oliphant, and T. Kammash.
9:27. The Current Quench Phase of a Plasma Disruption. Y. K. Peng, D. J. Strickler, and J. A. Holmes.
9:28. Stability of Thermal Barriers in Tandem Mirrors. C. Litwin and R. N. Sudan.
9:29. Parametric Decay in a Strongly Inhomogeneous Medium. K. Ko, A. Reiman, and K. Papadopoulos.
9:31. Radiation Cooling Instability in Zl Edge Plasmas. L. Montierth, R. Morse, and G. Sowers.
9:32. Ballooning and Ideal MHD Stability for the BYU Topolotron. D. L. Peterson.

9:33. Critical Pressure for Equilibrium and Stability in a Toroidal Stellarator Revisited. K. E. Weimer, J. L. Johnson, and J. M. Greene.
9:34. Eigenmode Equations for Axisymmetric Hot Electron Plasmas. T. M. Antonsen and Y. C. Lee.
9:35. A Self Consistent ECRH Power Deposition Calculation for Tandem Mirror End Plugs. D. G. Braun and G. A. Emmert.
9:36. Effects of Noise on the Standard Mapping. A. B. Rechester.
9:37. Computation of the Vacuum Magnetic Field in a Heliac Geometry. A. I. Shestakov and A. A. Mirin.
9:38. Ion Bernstein/Ion Acoustic Mode Coupling. T. Katsouleas, B. D. Fried, and G. Morales.
9:39. Stochastic Transport of High Energy Fusion Products Under Coulomb and Nuclear Scattering in Field Reversed Configurations. J. C. DeVearx and G. H. Miley.
9:40. Alfven Ion Cyclotron Instability in Sloshing Ion Plasmas. G. R. Smith.
9:41. Determination of Particle Transport in Asymmetric Toroidal Devices Using Magnetic Co-ordinates. G. K. Petravic and A. H. Boozer.
9:42. Macroscopic Stability of Large Aspect Ratio Mirrors with Energetic Particles. Y. C. Lee and T. M. Antonsen.
9:43. A Method for Constructing the WKB Connection Formulas for the Mode Conversion Tunnelling Problem. R. J. Kashuba and H. L. Berk.
9:44. Numerical Studies of Tandem Mirrors Using Reduced MHD. H. R. Strauss and S. Wollman.

WEDNESDAY, APRIL 28

8:30 - 10:30 ORAL SESSION 3A HILTON HOTEL
CHAIRMAN - WILLIAM NEVINS

8:1. Finite Orbit Saturation of the Stupakov Effect. W. A. Newcomb.
8:2. Fast Growing Trapped Particle Modes. M. N. Rosenbluth, H. L. Berk, D. E. Baldwin, H. V. Wong, and T. M. Antonsen.
8:3. Particle Simulations of Quasi Linear Diffusion in a Neutral Beam Driven Mirror Machine. B. I. Cohen, N. Maron, G. R. Smith, and W. M. Nevins.

10:30 - 11:00 COFFEE BREAK

11:00 - 12:00 ORAL SESSION 3B

11:1. Analysis of a Simple Transport Model. P. Rosenau.
11:2. Runaway Current Sustainment by Lower Hybrid Waves. V. S. Chan, C. S. Liu, D. K. Bhadra, R. W. Harvey, and F. W. McClain.
11:3. Recent Developments in EBT Stability Theory. D. A. Spong.

12:00 - 13:00 LUNCH

1:00 - 2:30 POSTER SESSION 3C

1:1. Neoclassical Tensor Transport Model for EBT Plasmas. M. Z. Caponi, M. A. Iskra, and T. Kammash.
1:2. Equilibrium Poloidal Field Distribution in Reversed Field Pinch Toroidal Discharges. D. Baker, L. Mann, and K. Schoenberg.
1:3. MHD Stability Analysis of ISX-B Discharges. L. A. Charlton, B. A. Carreras, J. A. Holmes, D. K. Lee, G. H. Nielson, D. S. Scott, and R. M. Wieland.
1:4. Was This the "Great Sign" Prophecied at Fatima?. R. McNally.
1:5. A Multi Region Fokker Planck Code. M. Baghaii and J. T. Woo.
1:6. Optimal Plasma Beta in an MHD Stable Field Reversed Configuration with Energetic, Large Orbit Ions. L. Sparks, R. N. Sudan, and J. M. Finn.
1:7. ICRF Mode Structures Due to Inhomogeneities. G. Morales, B. D. Fried, and T. Chiueh.
1:8. Heliac Stability. D. A. Monticello and R. L. Dewar.
1:9. Wave Propagation in Bumpy Torus. K. W. Whang and T. Shoji.
1:10. Effects of Impurity Radiation on Proto S-1C Speromak. Y. C. Sun, S. C. Jardin, R. A. Hulse, and M. Yamada.
1:11. Finite Temperature Effects in Free Electron Laser Amplifiers. L. Ibanez and S. Johnston.
1:12. Energetic Electron Tail Formation by Multiple Frequency Electron Cyclotron Resonance Heating. T. K. Samec and B. I. Hauss.
1:13. A Kinetic Wave Expansion for the Plasma Fields Generated by an External Coil in a Slab Geometry. B. D. McVey.
1:14. Can Tokamaks Succeed to Reach Fusion Domain. M. Cotsaftis.
1:15. Optimization of Steady State Beam Driven Tokamak Reactors. D. R. Mikkelsen and C. E. Singer.
1:16. Full MHD Equations vs. Reduced MHD Equations: A Comparison of Results. J. A. Holmes, B. A. Carreras, H. R. Hicks, V. E. Lynch, B. F. Masden, and T. C. Hender.
1:17. Velocity Shell Instabilities. R. W. Huff, J. M. Dawson, V. K. Decyk, I. Jechart, T. Katsouleas, C. F. Kennel, J. N. Leboeuf, R. M. Martinez, and D. Sentman.
1:18. Central Cell and Barrier Parameters in an Axisymmetric Tandem. R. A. Jong.
1:19. Mean Field Approach to Renormalized Perturbation Theory. R. V. Jensen and C. R. Oberman.
1:20. Simulation of Electron Temperature Profiles for Different Values of q. N. Sharky.
1:21. Saturation of Tilting of Particle Rings. R. V. Lovelace and C. B. Ruchti.
1:22. An Fokker-Plack Kinetic Approach for Collisional Particle Transport in a Field Reversed Theta Pinch. M. Y. Hsiao and G. H. Miley.
1:23. Heating of Tokamaks via Alfven Wave Excitation. C. E. Kieras and J. A. Tataronis.
1:24. Parametric Phenomena at Electron Cyclotron Resonance Heating of Tokamak Plasmas. V. Stefan and A. Bers.
1:25. Scattering of Lower Hybrid Waves: Solutions of the Radiative Transfer Equations. P. A. Andrews and F. W. Perkins.
1:26. Limit Cycles in Electron Cyclotron Heating. G. E. Guest.
1:27. Soliton Kinetic Effects. J. Morrison and J. D. Meiss.
1:28. Equilibrium Beta Limit for the Heliac Configuration. F. Bauer, O. Betancourt, and T. K. Chu.
1:29. An Analysis of Taylor's Theory of Toroidal Plasma Relaxation. V. Faber, A. B. White, and G. M. Wing.
1:30. Saturated Tearing Modes in Toroidal Geometry. G. Bateman and R. N. Morris.
1:31. Catastrophes in EBT - Neoclassical Electrons with ICRH. A. Punjabi, G. Vahala, and E. G. Harris.
1:32. Numerical Studies of Zero Net Current Torsatrons. O. Betancourt and F. Bauer.
1:33. Electron Bounce Resonance Heating in a Mirror Confined Plasma. K. C. Shaing and J. D. Callen.

1:34. Filamentation in High Beta Plasmas and Superconductivity. G. Vahala and L. Vahala.
1:35. Impurity Effects in a Small RFP Reactor. R. N. Byrne and D. Dobrott.
1:36. Modelling of Lower Hybrid Current Generations. E. J. Valeo, J. M. Ogden, and F. W. Perkins.
1:37. Model for Poloidal Divertors and Pump Limiters. D. Post, D. Heifetz, and G. K. Petravic.
1:38. Numerical Studies of the Coalescence of Ion Rings. P. M. Lyster and R. N. Sudan.
1:39. Electron Cyclotron Heating in Weakly Relativistic Finite Beta Plasmas. K. Audenaerde, J. Scharer, N. Lam, and J. Beyer.
1:40. Effects of a Constant Magnetic Field on Collisions. K. Matsuda.
1:41. Particle Transport Due to Electrostatic Turbulence in the Caltech Tokamak. P. C. Liewer, S. J. Zweben, and R. W. Gould.
1:42. Low Mode Number Stability of the Tandem Mirror. M. W. Phillips and J. D. Callen.

Resistive Stability in Cylindrical Geometry; Spheromak Application*

S. C. Jardin, J. DeLucia, A. Glasser†, R. C. Grimm,
D. Hewett††, C. Ryu, and G. Tesauro
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

The growth rates for resistive instabilities in a straight circular cylinder are computed by using two complementary methods. The first method solves the full resistive MHD equations as an initial value problem, utilizing zone packing around the mode rational surface. Resolution requirements limit this to values of the magnetic Reynolds number $S<10^7$. The second method employs boundary layer analysis and asymptotic matching,[1,2] most valid for $S \gtrsim 10^5$. The 6th order resistive inner region equations are solved numerically as an asymptotic boundary value problem. These solutions are matched onto a numerical solution of the ideal Euler equations in the outer region. The general matching condition involves even and odd parity modes with complex frequency, and includes both interchange and tearing forces. The inner region equations and matching condition have also been generalized to toroidal geometry with multiple rational surfaces. Each of these methods has independent checks on its accuracy. The results from these two methods agree to better than 1 in 10^3 in the overlap region $10^7>S>10^5$. As an application, we scan the parameter space of possible spheromak configurations by computing contours of the resistive growth rates in the continuous space formed by nq_o, na/R, for several values of the central pressure p_o and the poloidal mode number m. If we take the q-profiles to be parabolic in r, the least unstable configurations have $q_o R/a \sim 0.67$. We expect these straight system results to be fairly insensitive to toroidal corrections, as is the case for ideal instabilities in the spheromak.[3]

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†Physics Department, Auburn University, Auburn, Alabama 36849
††Los Alamos Scientific Laboratory, Los Alamos, New Mexico

1. B. Coppi, J. Greene, J. Johnson, Nucl. Fusion 6, 102 (1966).
2. A. H. Glasser, J. M. Greene, J. L. Johnson, Phys. Fluids 18, 875 (1975).
3. S. C. Jardin, PPPL-1861, (1982) to appear in Nucl. Fusion.

Oral Presentation

GLOBAL, NONLINEAR MAGNETIC RECONNECTION IN THE REVERSED-FIELD PINCH*

R. A. Nebel and E. J. Caramana, and D. D. Schnack
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Magnetic field line reconnection is of fundamental importance in fusion devices with large net internal current. Within the MHD model we have investigated the role of single-helicity, reconnecting modes on both the startup and sustainment phases of the Reversed-Field Pinch (RFP). Using a nonlinear resistive MHD code we find some analogs of the globally reconnecting modes that exist in tokamaks. However, important differences arise, principally from the dynamics of the toroidal field and the monotone decreasing nature of the RFP q profile.

During the startup phase of the pinch a mode is found that continues the process of anomalous radial penetration of a skin current once the q profile is monotone decreasing. This is analogous to the tokamak double-tearing mode. This mode tends to flatten both the q profile and the double-valued current profile, thus decreasing both the shear and the current gradients. During the sustainment phase of the pinch we find that if the current is too highly peaked on axis (which corresponds in the equilibrium to a low value of q on-axis and thus small magnetic shear) the RFP is unstable to current driven modes, with poloidal mode number m = 1, either with or without a plasma resonance. The mode with a resonance undergoes a sequence of two reconnections, one that combines flux tubes and eliminates the rational surface (as in the tokamak internal m = 1 "sawtooth" mode) and another that divides flux tubes and restores the rational surface to the plasma. The nonresonant mode undergoes only the second reconnection and introduces a previously nonexistent resonance into the plasma. The net result of both modes is to flatten current gradients and raise q on-axis, increasing shear. Thus, the RFP will produce a value of q on-axis that is neither too high nor too low.

One-dimensional transport calculations indicate that a thermal instability due to peaked electron temperature will cause the current to overpeak on-axis, just as is seen in the tokamak. In additon, these calculations show that during this "transport phase" the magnetic helicity ($K = \int A \cdot B dv$) is decayed preferentially over the magnetic energy ($W_M = \int B^2/8\pi \, dv$), thus leading to the aforementioned instabilities. These modes reverse this process and restore the proper balance of these quantities. Thus, we may have behavior in the RFP that resembles the internal sawtooth oscillations seen in tokamaks.

Experimental results from ZT-40M indicate that m = 1 activity is present. Comparison of our calculations with these observations will be presented. Also, relevance to maintenance of the reversed toroidal field (not seen in these 2-D studies) will be discussed.

*Work performed under the auspices of the USDOE.

ORAL PRESENTATION REQUESTED

EQUILIBRIUM AND STABILITY OF ELONGATED FIELD-REVERSED-CONFIGURATIONS*

R. L. SPENCER, D. W. HEWETT, AND J. L. SCHWARZMEIER
Los Alamos National Laboratory, Los Alamos, NM 87545
D. C. BARNES Institute for Fusion Studies, University of Texas, Austin, TX 78712
C. SEYLER Cornell University, Ithaca, New York 14583

The theoretical study of field-reversed-configurations (FRC) has been hampered by the difficulty of computing highly elongated equilibria of the kind observed in field-reversed-theta-pinch experiments. To better understand the nature of this difficulty, we looked for solutions of the Grad-Shafranov equation with straight-conducting-wall boundary conditions and with the simple profile $dp/d\psi = cH(\psi)$, where H is the Heaviside function. This is the same profile used by Berk, Hammer, and Weitzner, but their equilibria do not satisfy straight-wall boundary conditions. After we solved this simplified problem by a Green's function method, the source of the difficulty was apparent: elongated equilibria are found near a bifurcation point. Furthermore, the elongation is sharply singular at the value of c where z-independent solutions of the equilibrium equation satisfy the average-beta condition. This means that looking for long equilibria by varying parameters in pressure profiles likely won't work. To overcome these problems for general pressure profiles where the Green's function method is inefficient, we compute on an r-z mesh using a Dynamic-ADI algorithm and a global constraint (the toroidal current in the computing region is specified). For the pressure profile $p = s\ \tanh(t\psi+u)$, elongated equilibria exist in the region of the (p(separatrix)/p(vortex) , r(separatrix)/r(wall)) parameter space shown in Fig. 1. This pressure profile can, for suitable s, t, and u, produce radial profiles of pressure and magnetic field matching those observed in experiments. Figures 2 and 3 show two of the equilibria obtained. FRC's have been predicted theoretically and by linear and non-linear simulations to be MHD unstable to tilting; but tilting is not observed in experiments. It has been suggested that the observed stability of FRC's is due either to MHD profile effects or to kinetic effects. We have numerically implemented a kinetic theory in which the MHD and kinetic aspects of the problem are explicitly separated. We find that tilting can be stabilized in MHD by making the flux surfaces sufficiently racetrack-like. (See Fig. 3.) The shaded region in Fig. 1 indicates stable equilibria. These stable equilibria are, however, unlike those observed in experiments. This suggests that the observed stability of existing FRC's is due to kinetic effects.

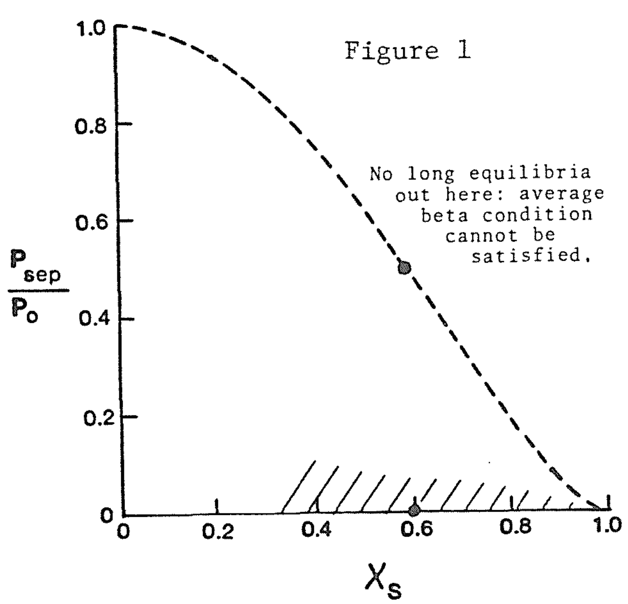

Figure 1

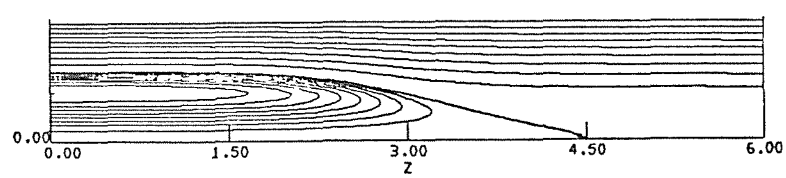

Figure 2; p_{sep}/p_o = .5; tilt unstable

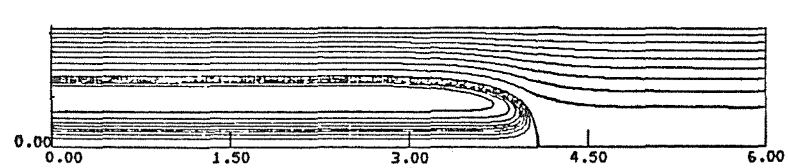

Figure 3; p_{sep}/p_o = 0.; tilt stable

*Work performed under the auspices of USDOE.

Drift Orbits in Toroidal Systems With Imperfect Magnetic Surfaces*

R. B. White and A. H. Boozer
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

A Hamiltonian formalism has been developed for the drift orbit trajectories of particles in toroidal systems in arbitrary steady state magnetic and electric fields possessing magnetic surfaces. The canonical variables of this formalism are simply related to the magnetic coordinates. The modifications to the drift orbits due to magnetic perturbations producing partial destruction of the magnetic surfaces are also given.[1,2] A numerical code based on these equations is used to investigate the modification of neoclassical diffusion due to the onset of stochasticity. Three qualitatively different regimes are observed. Well below stochastic threshold[3] the diffusion is given by the neoclassical value. Near stochastic threshold, where magnetic surfaces are beginning to break up, a significant fraction of space is filled with magnetic islands, which give rise to enhanced transport much in the way banana orbits contribute to neoclassical diffusion. This island-banana diffusion does not significantly affect the ions because of their large neoclassical diffusion rate, but it does increase the electron diffusion rate. Finally, well above stochastic threshold the particles diffuse following the stochastic field, the diffusion rate given by quasilinear theory.[4]

Neutrality of the plasma would of course not permit large differences in electron and ion diffusion to occur, but similar modification of electron heat transport is to be expected. Direct association of the observed mechanism with anomalous electron energy confinement in tokamaks must await more detailed simulations using observed mode spectra.

*This work was supported by United States Department of Energy Contract No. DE-AC02-76-CHO3073.

1. R. B. White, A. H. Boozer, and R. Hay, Phys. Fluids Letter, p. 575 March 1982.
2. A. H. Boozer and R. B. White, PPPL-1872.
3. V. Chirikov, Phys. Rep. 52, 263 (1979).
4. M. N. Rosenbluth, R. Z. Sagdeev, J. B. Taylor, and G. M. Zaslavsky, Nucl. Fusion 6, 297 (1966).

Oral Session

TOROIDAL STELLARATOR FIELDS WITH NESTED MAGNETIC SURFACES

John R. Cary
Institute for Fusion Studies
University of Texas
Austin, Texas 78712

Stellarator fields (vacuum magnetic fields with rotational transform) with a dense set of nested magnetic surfaces are rigorously known to exist only for systems with straight helical symmetry. For practical (i.e. toroidal) systems no analytic flux invariant is known. Surface of section analyses routinely show the existence of fairly dense magnetic surfaces out to some limiting surface with mean radius and rotational transform depending on the helical current, the toroidal field, and the winding law. Outside of that surface, the magnetic fields are unconfined; they wander away due to stochastic effects.

The present work is devoted to obtaining an understanding and, ultimately, the elimination of stochasticity in toroidal stellarator fields. We begin by applying a perturbation analysis to the Hamiltonian description of field-line flow to calculate the lowest order flux invariant and the islands produced by resonances caused by toroidal coupling. We find that lowest order perturbation theory gives a good approximate analytic flux invariant. We also find that the Chirikov (resonance-overlap) criterion accurately predicts the rotational transform of the last good magnetic surface observed in a surface of section plot.

This motivates us to try to eliminate the stochasticity inducing resonances by superimposing several magnetic fields of different primary helicities. We find the amplitudes of the required additional magnetic fields by imposing the requirement that resonant denominators vanish from the perturbation theory in every order. The results of a simplified, first-order theory are encouraging. For CLEO-like parameters (ℓ=3, m=7, $\varepsilon \cong 0.1$) the superposition of additional harmonics increases the rotational transform of the last surface from 0.8 to 1.2, a 50% improvement.

Work supported by DOE Grant No. DE-FG05-80ET-53088.

Oral Session

Neoclassical Transport Equations Including Flows and Bootstrap Current in Nonaxisymmetric Toroids*

K.C. Shaing and J.D. Callen

Nuclear Engineering Department, University of Wisconsin
Madison, Wisconsin 53706

Neoclassical transport theory for nonaxisymmetric toroids is developed in a manner similar to the fluid approach developed for axisymmetric tokamaks. The flux-friction relationships are similar to those obtained in an axisymmetric system except that there is an additional, nonambipolar flux ($\sim v_D^2/\nu_{eff}$ for $\nu_{eff} < \omega_b$) driven by the toroidal viscosity. General transport equations for particles, momentum and heat are developed in Hamada coordinates. The transport equations include self-consistent flows, bootstrap currents and flux surface movements relative to a computational grid.

Parallel (to the magnetic field) viscosity in both the Pfirsch-Schluter and banana regimes is calculated and used in the parallel momentum balance equation to obtain the parallel flows and bootstrap current. It is found that both the parallel flows and bootstrap current can be reduced if the magnetic field bumpiness in the toroidal direction is increased. The basic mechanism responsible for this reduction is the finite viscosity due to collisions and magnetic pumping. In an axisymmetric tokamak the poloidal component of the diamagnetic flow tends to vanish because of the viscous damping. As the toroidal bumpiness of the magnetic flux surfaces increase, the toroidal component of the diamagnetic flow tends to vanish and this causes the parallel flows and bootstrap current to be reduced. In the Pfirsch-Schluter regime the self-consistent parallel flow velocity in a rippled tokamak [$B = B_o (1 - \varepsilon \cos\theta - \delta \cos N\phi)$] is

$$u_{\parallel} = + \frac{1 - N^2\delta^2}{1 + N^2 q^2 \delta^2/\varepsilon^2} u_{\parallel ax}$$

where $u_{\parallel ax} = - (cT/eB_p)(n'/n)$ is the usual axisymmetric flow velocity. Both the parallel flow velocity and the bootstrap current are reduced from their axisymmetric values for $Nq\delta > \varepsilon$; they become a factor B_p^2/B_T^2 smaller and opposite in sign for large δ S. Similar effects and reductions occur in the banana regime, and for stellarators. An alternative calculation of the bootstrap current based upon a kinetic approach is presented in a companion paper at this conference by H.E. Mynick and arrives at similar conclusions regarding bootstrap currents in stellarators.

1. S.P. Hirshman and D.J. Sigmar, Nuclear Fusion 21, 1079 (1981).

*This work was supported by the U.S. Department of Energy Contract No. DE-AC02-80ER53104.

Locally Coupled Evolution of Wave and Particle Distributions in General Magnetoplasma Geometry

A. N. Kaufman, C. Grebogi,* and S. W. McDonald, Lawrence Berkeley Laboratory

Self-consistent kinetic equations for wave-action density $J(\underline{x},\underline{k};t)$ and for particle oscillation-center density $F(\underline{x},\mu,P;t)$ are derived, with local gyroresonant and nonresonant interaction in nonuniform magnetoplasma of general geometry. The waves have arbitrary polarization and are assumed incoherent, with short wave-length (of order gyroradius). Their propagation is governed by the ray Hamiltonian $\omega(\underline{x},\underline{k};F)$, obtained from the local susceptibility tensor $\underset{\approx}{\chi}(\underline{k},\omega;\underline{x},t;F)$. The oscillation-center density evolves via the ponderomotive Hamiltonian $H(\underline{x},\mu,P;J)$, in the g.c. representation: $\underline{x}$=g.c. position, μ=magnetic moment, P=parallel momentum. Explicit expressions are obtained for $\underset{\approx}{\chi}$ and H; their common resonant denominator is $\omega-\ell\dot{\theta}-\underline{k}\cdot\dot{\underline{x}}$, where the gyrofrequency and the g.c. velocity are nonlinearly obtained from H. The irreversible gyroresonant interaction appears consistently in both kinetic equations: as linear wave growth/damping and emission in the J-equation, and as quasilinear diffusion (in $\underline{x},\mu$,P-space) and radiation reaction in the F-equation. The formulation includes spatial gradients of F, magnetic curvature, torsion, and shear, and electric drifts. The evolution equations obey an energy-conservation law, momentum conservation in the presence of symmetry, and an entropy theorem. The latter indicates an approach to a Gibbs distribution $F\sim\exp(-H/T)$ at the wave temperature $T=J\omega$, without the need for collisions. Applications to turbulent transport and extensions to nonlinear processes are planned.

The derivation of the J-equation utilizes the Weyl-symbol calculus for evolution of the electric local spectral tensor in 8-dimensional $(\underline{k},\omega,\underline{x},t)$-space. The derivation of the F-equation utilizes Lie transforms (1) and the symplectic g.c. representation (2) for 5-dimensional particle phase-space. The coupled equations may be considered as a generalization of Dewar's oscillation-center theory (3).

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3. R. Dewar, Phys. Fluids 16, 1102 (1973).

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*Present address: Laboratory for Plasma and Fusion Energy Studies, University of Maryland.

ALPHA PARTICLE DRIVEN COMPRESSIONAL ALFVÉN WAVE INSTABILITY IN A TANDEM MIRROR REACTOR*

James D. Hanson and Edward Ott
Laboratory for Plasma and Fusion Energy Studies
University of Maryland
College Park, Maryland 20742

Because their energies greatly exceed the plug potential, fusion reaction alpha particles in a Tandem Mirror Reactor will be mirror confined rather than electrostatically confined by the end plugs. Hence, the alpha particle distribution function will have a loss cone. This anisotropy in the distribution function is shown to destabilize compressional Alfvén waves in the central section of a Tandem Mirror Reactor. The guiding center plasma equations are used to determine the radial model structure of the compressional Alfvén waves in cylindrical geometry. The growth rate is calculated from the perturbed current and electric field of the wave. Destabilization of the wave occurs due to a cyclotron resonance of the alpha particles. The resonant interaction of the wave with the alpha particles will pitch-angle scatter the alphas into the loss cone effectively widening the loss cone. In a typical fusion plasma ($T_i = T_e = 20$ keV, $\beta = .4$, $B_{VAC} = 3T$) we find 54% of the alpha particle energy is lost when the effects of the instability are included, whereas only 17% is lost without the instability.

*Work supported by Department of Energy.

Poster

POSTER SESSION

ENHANCEMENT IN THE ION THERMAL CONDUCTIVITY IN NEUTRAL-BEAM HEATED TOKAMAKS*

C. S. Chang
General Atomic Company
San Diego, California

ABSTRACT

A mechanism for significant enhancement of the neoclassical ion thermal conduction has been discovered for the neutral beam heated tokamaks. Injection of high energy beam particles into a tokamak produces a poloidally varying electrostatic potential that is higher on the outside than the inside of the torus. As a result, electrostatic trapping becomes as important as magnetic trapping in determining the neoclassical coefficients. As large as a factor of two enhancement over the usual neoclassical ion thermal conductivity is expected for PDX with four beam operation or ISX-B with toroidal rotation speed approaching the ion thermal speed. Such an enhancement appears consistent with recent experimental observations.[1,2] Moreover, the large poloidal variation in the electron density observed[1] in PDX is consistent with the poloidal electrostatic-potential variation predicted by the theory. The effects on the electrical resistivity will also be discussed.

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[2]Swain, D. W., et al., Nucl Fusion 21, 1409, 1981.

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TIME EVOLUTION OF THE FRC: SPINUP THROUGH DISRUPTION*

D. S. Harned and D. W. Hewett
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

The post-formation time evolution of the FRC is studied with a fully nonlinear, two-dimensional, hybrid (particle ions; fluid electrons) simulation code.[1] Simulations are initialized with nonrotating FRC equilibria satisfying the average β condition.[2] Particles having guiding centers on open field lines are lost from the system on approximately an ion thermal transit time.

It has been previously shown[3] that to leading order particle loss can lead to plasma rotation. Our simulations demonstrate that this initial spinup of the plasma occurs at a rate predicted by the loss of gyroaveraged particle angular momentum from the initial equilibrium. However, this behavior changes substantially after the first few percent of plasma inventory has been lost. The initial spinup is localized near the plasma edge. The developing ion current at the separatrix reduces the confining radial electric field, which in turn reduces the $\underset{\sim}{E} \times \underset{\sim}{B}$ momentum of particles in the separatrix region. Hence, each particle lost subsequently will carry less $\underset{\sim}{E} \times \underset{\sim}{B}$ momentum. As a result, ion rotation near the separatrix reaches a maximum value after which further loss of particles produces significantly less rotation.

The ion rotation remains sharply peaked near the separatrix for μs timescales. The velocity shear is later observed to be suddenly lost when the ion rotation propagates through the field null into the bulk of the plasma. When this loss of velocity shear occurs, measurements of velocity near the plasma edge would indicate a decrease in ion rotation, as seen in the STP-L experiment at Nagoya.[4] Additionally, after this time the spinup per particle lost is again observed to increase. We find that the length of time for the rotation to propagate into the bulk of the plasma increases for equilibria with increasing values of R/ρ_i. After the plasma angular momentum has increased sufficiently and the rotation has propagated across the radius, the plasma eventually reacts with the m = 2 rotational instability that has been found to terminate the stable period in the FRC experiments. For one case with parameters similar to FRX-B at Los Alamos ($R/\rho_i = 15$, $\beta_s = .5$, $x_s = .5$), we observe the onset of the m = 2 instability when 35% of the plasma inventory has been lost, after approximately 16 μs.

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4. K. Hirano, private communication.

*Work performed under the auspices of the USDOE.

ORAL PRESENTATION REQUESTED

DRIFT WAVE TURBULENCE IN A LOW ORDER $\underset{\sim}{k}$ SPACE

Wendell Horton and Paul Terry
Institute for Fusion Studies
University of Texas
Austin, Texas 78712

A two fluid model for drift waves incorporating (1) $\underset{\sim}{E} \times \underset{\sim}{B}$ convection and the full polarization drift in the nonlinear ion dynamics and (2) linear dissipation in the electron dynamics is studied in a low order isotropically truncated $\underset{\sim}{k}$ space first introduced by Kells and Orszag[1] in a study of neutral fluid turbulence. Conclusions obtained in previous three-wave studies[2] with the same dynamical model are tested in this more realistic model of turbulence.

In the multi-mode problem we obtain a criterion for the saturation of the instability expressed in terms of the rate of phase space contraction. We identify weakly and strongly unstable regimes while examining the variation of the saturation amplitudes $\phi(\underset{\sim}{k})$ and the spectral line widths $\nu(\underset{\sim}{k})$ as a function of the degree of instability. The amount of spectral broadening attributable to the dissipation is investigated. The stationary wavenumber spectra are studied for their stability and the rate of isotropization due to the nonlinear coupling proportional to $(\underset{\sim}{k}_1 \times \underset{\sim}{k}_2 \cdot \hat{b})^2$. Symmetries in $\underset{\sim}{k}$ space are noted, and the root-mean-square fluctuation level is compared with the mixing length theory.

1. L.C. Kells and S.A. Orszag, Phys. Fluids 25, 162 (1978).
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ORAL SESSION

STRANGE ATTRACTORS IN CRISIS

Celso Grebogi and Edward Ott
Laboratory for Plasma and Fusion Energy Studies
University of Maryland
College Park, Maryland 20742

James A. Yorke
Institute for Physical Sciences and Technology and
Department of Mathematics
University of Maryland
College Park, Maryland 20742

Chaos in dissipative dynamical systems is associated with the appearance of strange attractors.[1] Applications of concepts in this field are beginning to appear in plasma and fusion theory problems. In this paper we discuss a prevalent phenomenon occuring in a wide variety of problems where strange attractors exist. Namely, as a parameter of the system is varied sudden qualitative changes in the behavior of the system can occur. We use the word crisis to describe such changes. Here we describe the general nature of such crises, the context in which they occur, and give simple easily understandable (but nontrivial) examples. Our examples include the simple one-dimensional quadratic map,[2] the two-dimensional attractor of Henon,[3] and the complex map[4] $z^2 + C \to z$. For the case of the one-dimensional quadratic map we find sudden widenings of the chaotic region, and we investigate scaling properties near the crisis point. For the case of the Henon map, we find that the crisis destroys the strange attractor. For the case of the complex map (relevant, for example, to systems of four ordinary differential equations), we exhibit the interesting phenomenon of an attractor whose region of attraction is bounded by a fractal curve, and we investigate how this attractor disappears as the parameter C is varied. An example occurring in plasma wave turbulence theory will also be cited.

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HIGH-β TANDEM MIRROR EQUILIBRIA IN THE PARAXIAL LIMIT*

T. B. Kaiser, B. McNamara, L. D. Pearlstein, and P. Willmann
Lawrence Livermore National Laboratory, University of California
Livermore, California 94550

Strauss has recently adapted the reduced MHD technique used in tokamak and stellarator studies to the calculation of tandem mirror equilibria in the paraxial limit.[1] As originally formulated, his scheme used Eulerian coordinates and solved separate initial value problems on the distinct time scales appropriate to perpendicular pressure balance (compressional Alfvén waves) and perpendicular momentum balance (shear Alfvén waves).

We take advantage of the fact that an analytic solution is available on the slow time scale to avoid the necessity of solving the associated initial value problem. We then recast the shear Alfvén problem in Lagrangian (flux) coordinates, and solve by common techniques. We include the possibility of a vacuum region external to the plasma in order to apply realistic boundary conditions.

High-β equilibria for the TMX-Upgrade experiment will be presented if available, as well as comparisons of moderate-β equilibria with equivalent calculations by the existing β-expansion TEBASCO code.

1. H. R. Strauss, Bulletin of the A.P.S. 26, 958 (1981).

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

1C7

ELECTRON THERMAL TRANSPORT IN PLASMAS WITH AUXILIARY HEATING

P.T. Bonoli, R. Englade, and B. Coppi
Massachusetts Institute of Technology, Cambridge, MA, 02139

A form for the electron thermal diffusion coefficient of the type first proposed by Coppi and Mazzucato[1] has been shown to account for experimental observations in a wide variety of ohmically-heated toroidal discharges. A modified form of this diffusion coefficient has been advanced, appropriate to situations in which non-ohmic auxiliary heating is important.[2]

The magnitude of the "non-ohmic" coefficient is typically greater than that of the "ohmic" coefficient. It is also found that a degradation of the electron energy confinement time is consistent with situations where the power deposition profile to the electrons (due to auxiliary heating) departs from the profile that would be obtained for an ohmically heated case (typically a Gaussian).

We have used both forms of the diffusion coefficient in transport code simulations of lower hybrid heating on the Alcator C tokamak and lower hybrid current drive in the Versator II device.[3] It is found that plasma heating associated with the "non-ohmic" coefficient is considerably less than that which occurs with the ohmic diffusion coefficient. In addition, it has been found necessary to include the "non-ohmic" diffusion coefficient in simulations of current drive in Versator II, in order to reproduce the experimentally observed changes in the central electron temperature.[4]

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LOW m NUMBER STABILITY OF THE ELMO BUMPY TORUS

K.D. Cogswell and J.P. Freidberg
Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

The stability of macroscopic low m number modes is investigated in the context of the Vlasov Fluid model which treats both the hot electrons and ions kinetically, and the background electrons as a fluid. A simple perturbed momentum balance equation, expressed in terms of the familiar MHD plasma perturbation, $\underline{\xi}$, is derived for the EBT plasma. This equation describes the effects of a finite bumpy field geometry, hot electron and/or ion rotation, and the usual finite Larmor radius terms, as well as terms representing the inherently kinetic response of the hot electrons in the regime $\omega_{*e} >> \omega$, including compressibility. A variational principle is derived, and familiar techniques of MHD stability analysis are applied, leading to predictions of stable EBT operation for parameters in good agreement with experiment.

HIGH-FREQUENCY INSTABILITIES IN HOT-ELECTRON PLASMAS*

Yu-Jiuan Chen, William M. Nevins, and Gary R. Smith
Lawrence Livermore National Laboratory, University of California
Livermore, California 94550

Instabilities with frequencies in the neighborhood of the electron cyclotron frequency Ω are of interest in determining the stable operating regime of hot-electron cells in tandem mirrors. Extending previous work on these instabilities,[1] we are developing a code that solves the electromagnetic dispersion relation governing waves in a uniform plasma. We allow for an arbitrary direction of wave propagation. Electron distribution functions suggested by recent Fokker-Planck studies[2,3] of electron-cyclotron-resonance heating in a magnetic-mirror field are modeled by superposing five electron components with various densities and temperatures. Each component has an anisotropic, loss-cone distribution.[4] For TMX-Upgrade parameters, the maximum temporal growth rates of both whistler and upper-hybrid loss-cone (UHLC) modes are less than 0.004 Ω, if the average temperature anisotropy $\langle T_{\parallel}\rangle/\langle T_{\perp}\rangle \gtrsim 0.4$ and $\omega_{p,tot}^2/\Omega^2 \lesssim 0.55$. Spatial growth rates are of order 0.1 cm^{-1} and 1 cm^{-1} for the whistler and UHLC modes, respectively. We discuss the extension of this work to find the convective/absolute instability boundaries.

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4. J. D. Callen and G. E. Guest, Nucl. Fusion 13, 87 (1973).

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1C10

THEORY AND SIMULATION OF MICROINSTABILITIES IN FIELD REVERSED CONFIGURATIONS

N. T. GLADD
JAYCOR
San Diego, California

A. G. Sgro, C. Lilliequist, and D. Hewett
Los Alamos National Laboratory
Los Alamos, New Mexico

Anomalous transport associated with microinstabilities is thought to play an important role in the behavior of field reversed configurations. Specifically, the scattering of particles (and their angular momenta) across the separatrix between closed and open field lines results in the spinup of the confined plasma. This spinup eventually triggers an m = 2 instability that terminates confinement. We use two recent developments--nonlocal, electromagnetic stability analyses of realistic plasma profiles and the use of finite electron mass hybrid simulation techniques in the low drift velocities typical of experiments--to study the microstability properties of the separatrix region of field reversed configurations in a detail heretofore impossible. In particular, we examine the lower-hybrid-drift instability, which has long been thought to be important in pinch plasmas and which has recently been directly observed in the German Interex theta pinch.

Nonlinear Evolution of 2D Lower-Hybrid-Drift Wave Turbulence

J.D. Huba
Naval Research Laboratory
Washington, D.C. 20375

J.F. Drake and P.N. Guzdar
Science Applications, Inc.
McLean, Virginia 22102

The lower-hybrid-drift instability is believed to be important in many space and laboratory plasmas because it can provide anomalous transport of particles, momentum and energy. Although the linear theory of the instability is well understood, the nonlinear theory is not as well developed. In this regard, we have derived a wave-wave coupling equation which describes the nonlinear evolution of modes in the plane transverse to the magnetic field, i.e., 2D turbulence. The equation is similar to the Hasegawa-Mima equation for drift wave turbulence[1] except that the roles of the electrons and ions are reversed, lower-hybrid-drift wave turbulence is strictly two dimensional, and we include realistic sources and sinks of energy based upon linear theory. The equation is solved using a spectral method code developed by Fyfe, Joyce and Montgomery.[2] The following results are to be presented: the time evolution of selected individual modes; the instantaneous and time averaged power spectra, i.e., $|\phi_k|^2$ vs. k^2 and the evolution of the wave spectra as a function of k_x, k_y and $|\phi_k|^2$. Applications to laboratory and space plasmas will be discussed.

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2. D. Fyfe, G. Joyce and D. Montgomery, J. Plasma Physics 17, 317 (1977).

Rotational Stability of Tandem Mirrors*

D. A. D'Ippolito and J. P. Freidberg†

Science Applications, Inc.
Plasma Research Institute
934 Pearl Street
Boulder, Colorado 80302

The solution of a model problem is presented in which the destabilizing influence of mirror curvature on low-m rotational modes is clearly illustrated. The starting point of the calculation is a stability equation[1] derived from the Vlasov-Fluid model for a long-thin axisymmetric mirror rotating with angular velocity $\Omega(r)$. This partial differential equation includes the destabilizing effects of curvature and rotation and the stabilizing influence of FLR effects; it is valid for arbitrary mirror ratio R and azimuthal mode number m.

The equation is separable in the small mirror ratio limit, and the resulting system of ODE's can be solved numerically by standard shooting techniques. We have computed the rotational-ballooning stability boundaries in this limit for the rigid-rotor model. The results show that the threshold value of Ω for instability is greatly reduced by the addition of the curvature drive terms. The relevance of our results to TMX, where an $m = 1$ rotational mode has been observed,[2] is discussed.

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†Permanent address: Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.

[1] D. A. D'Ippolito and J. P. Freidberg, Bull. Am. Phys. Soc. 26, 901 (1981).

[2] E. B. Hooper, Jr., G. A. Hallock and J. H. Foote, LLL Report #UCRL-86589.

MHD Analysis of PDX Discharges*

R. Izzo, W. Park, D. A. Monticello, K. McGuire,
D. Buchenauer, and H. R. Strauss†
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

A reduced set of resistive MHD equations are solved numerically in three-dimensions to study the stability of PDX plasmas. Two cases can be treated by the code. For high beta plasmas, the equations used are correct to leading order in inverse aspect ratio, $\varepsilon = a/R_o$. This version of the code (HIB) was used previously.[1] For low beta plasmas, the equations are modified to include all terms to next order in ε self consistently. In addition, the low beta momentum equation yields the Grad-Shafranov equation correct to all orders in ε. The low beta equations permit us to study a greater range of PDX discharges with improved accuracy. Both sets of equations have an energy integral. Recent applications of the high beta equations to discharges with $q(a) \approx 2$ are presented. We compare results from the low beta equations with those obtained from high beta scaling. Also, high-n, resistive ballooning analyses of PDX discharges are performed.

*This work supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

†New York University, Courant Institute, 251 Mercer Street, New York, NY

1. W. Park, D. A. Monticello, R. B. White, K. McGuire, and M. Reusch, Proc. U.S. - Japan Theory Workshop on 3-D MHD Studies for Toroidal Devices, Oak Ridge, TN, (October, 1981).

Poster Session

Nonresonant Electron Transport in EBT*

D. E. Hastings and D. A. Spong
Oak Ridge National Laboratory, Oak Ridge, Tennessee

Abstract

For the experimentally measured parameters in EBT, the electrons in the core plasma are nonresonant, that is the average $\underline{\nabla}B \times \underline{B}$ and $\underline{E} \times \underline{B}$ precessional drifts are in the same direction. Analytic transport rates exist for the electrons for the case where the ambipolar field is large relative to the plasma thermal energy[1]. For finite fields, the diffusion coefficients have been calculated numerically[2]. We have developed an analytic expansion away from the large field case which provides corrections to the results of Ref. 1 for finite fields. We compare these expressions with the numerical calculations for parameters of experimental interest and show that we can obtain a substantial improvement over the Kovrizhnykh results.

*Research sponsored by the Office of Fusion Energy, Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

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This abstract to follow "Resonant Ion Transport in EBT."

TIME ACCELERATION OF TRANSPORT EQUATIONS FOR GENERATING STEADY-STATE SOLUTIONS*

W. A. Houlberg and S. E. Attenberger

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

For many applications the steady-state solution of the transport equations is desired. However, when the equations are cast in a time-dependent form the steady-state solution is approached on the slowest timescale while the timestep is generally governed by the fastest timescale. To alleviate this problem the transport equations can be modified with time in each equation cast in dimensionless form by normalizing to a characteristic timescale for that equation. For example, the electron energy equation is normalized to the electron energy confinement timescale and the magnetic flux diffusion equation to the resistive skin timescale. In this way each equation is advanced toward steady-state at the fastest rate possible. Different radial zones can also be normalized to different timescales. This is particularly advantageous for the scrape-off region where particle and energy flow is governed by losses along the magnetic field lines and timescales are dictated by the parallel flow. But time merely becomes a parameter for advancing the equations to steady-state and real-time relationships between parameters are lost.

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AMBIPOLARITY OF HIGH ENERGY COLLISIONLESS IONS IN EBT*

E. F. Jaeger, D. E. Hastings, J. S. Tolliver,
and C. L. Hedrick
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Conventional neoclassical transport theory has been unable to account for the loss of low energy bulk ions from the deep potential wells observed in EBT. We consider an alternate model in which bulk ion heating rather than pitch angle scattering determines the ion loss rate and hence the ambipolar electric field. Assuming that ion heating produces a high energy ion tail in the collisionless neoclassical banana regime, quasi-charge neutrality gives a first order ordinary differential equation for the ambipolar electric field $E(\rho)$ where ρ is the radius at which a flux surface intersects the mirror midplane. Parabolic density and temperature profiles are assumed. In the limit of very small ion tail density and collisionality, the midplane potential scales with magnetic field as $\phi'(\rho) \propto - B'(\rho)$. Deviations from this scaling for finite tail density and collisionality are considered along with sensitivity to boundary conditions on the electric field near the plasma edge.

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This abstract to follow "Nonresonant Electron Transport in EBT."

1C17

EBT TRANSPORT AND ORBITS FOR PEDESTRIANS*

C. L. Hedrick, D. E. Hastings,
E. F. Jaeger, and J. S. Tolliver
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

The 200 kilowatt ECH experiments on EBT-S in the past year suggests that the resonant ion collisionality is low enough that banana transport may be important. This has led to the development of tractable expressions for the resonant ion transport coefficients for the entire range of resonant ion collisionality (banana to plateau inclusive).[1] These transport coefficients include derivatives of the ambipolar electric field for all collisionality but the extreme plateau limit. This causes the electric field to be described by a differential equation rather than the algebraic equation encountered in the plateau limit.[2] Initial results indicate improved agreement with experimental measurements of the electric field. Here, simplified derivations of the various limits for both electron and ion transport coefficients are given; some of the present short-comings of the theory are enunciated; and the relations to the EBT-P program are indicated.

*Research sponsored by the Office of Fusion Energy (OER), U.S. Department of Energy under Contract W-7405-eng-26 with the Union Carbide Corporation.

[1] J. S. Tolliver, et al., "Resonant Ion Transport in EBT," to be presented at this meeting.

[2] E. F. Jaeger, et al., "Ambipolarity of High Energy Collisionless Ions in EBT," to be presented at this meeting.

This abstract to precede "Resonant Ion Transport in EBT"

1C18

THEORY OF TWO-POINT CORRELATION FOR TRAPPED ELECTRONS AND THE FREQUENCY SPECTRUM OF DRIFT WAVE TURBULENCE IN TOKAMAKS

P.H. Diamond and P. Terry
Institute for Fusion Studies
University of Texas
Austin, Texas 78712

A theory of two point correlation[1,2] for trapped electrons is presented together with its implications concerning the frequency spectrum of drift wave turbulence in tokamaks. Specifically, exploiting the ballooning representation, a nonlinear equation for the bounce-averaged electron distribution function is used to construct and renormalize the two point correlation equation. An approximate solution of the two point equation is obtained and used to determine the incoherent (non normal mode-like) correlation function and to derive an integral equation for the incoherent potential spectrum. An analysis of the spectrum equation yields approximate analytic expressions for the frequency line width ($\Delta\omega_k$) and the (enhanced) growth rate for the turbulent regime. A saturation criterion is also obtained. The saturation criterion equation is used to derive a one-dimensional integral equation for the wave number spectrum $\langle\phi^2\rangle_{k_\theta}$. The effect of frequency broadening ($\Delta\omega_k \neq 0$) on ion compton scattering (as a saturation mechanism) is discussed.

The principal results of this investigation are:

1. the construction of a renormalized two point theory in the ballooning representation.
2. the identification of a novel mechanism for enhanced accessibility of expansion free energy. This mechanism has no analogue in the one point (mode) theory.
3. the determination of an analytic expression for $\Delta\omega_k$. For typical parameters, $\Delta\omega_k \sim \omega_k$ is found.
4. the determination of the effect of frequency broadening on nonlinear wave-particle scattering. For certain cases, nonlinear ion Landau damping is significantly enhanced.

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Work supported by DOE Grant No. DE-FG05-80ET-53088.

1C19

SPEED: A CODE FOR CALCULATING SCALAR PRESSURE EQUILIBRIA IN THE EBT DEVICE*

W. H. Miner and A. Kadish
Science Applications, Inc.
McLean, VA 22102

and

H. Grad
New York University
New York, NY 10012

SPEED is a three dimensional, finite beta, scalar pressure, equilibrium code for EBT. The algorithm employed is an iterative procedure due to H. Grad**, applicable to magnetic confinement devices which have closed field lines.

The iteration alternates between the calculation of the 3D flux (pressure) surface geometry and 1D distribution of pressure on these surfaces consistent with force balance. The pressure profile, $P = P(V,\psi,\psi')$, is prescribed, where V is the volume within the flux surface, ψ is the flux enclosed and ψ' is the derivative of the flux with respect to the volume. Results for various types of pressure profiles will be presented.

Models for the effects of the high beta electron rings on the scalar pressure core plasma are being investigated. There are several models for these effects which could be included in the present equilibrium calculation with only slight modification to the existing code. A fully self-consistent equilibrium calculation for the ring-core plasma system will require more extensive modifications of SPEED. These models will be discussed.

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* Work supported by ORNL under contract 62B-13819C9(62X-32).

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The Whistler Instability Driven by Relativistic Lost-Cone Electron*

K. T. Tsang

Science Applications, Inc.
Plasma Research Institute
934 Pearl Street
Boulder, Colorado 80302

The hot electron ring formed by electron cyclotron heating plays an important role in the confinement of EBT plasma. In a tandem mirror, a hot, anisotropic electron component can be employed either as a potential-depressing component in a thermal barrier, or as a pressure-enhancing component in an MHD anchor. Stability of this hot electron component with respect to high frequency modes, such as the whistler, is crucial to the energy balance of these devices.

The whistler dispersion relation for a relativistic hot electron with a loss cone is derived. As expected, a loss cone distribution enhances the anisotropy and so is destabilizing. This observation is confirmed numerically. Relativistic effects tend to broaden the wave-particle resonance which drives the instability whenever anisotropy persists.[1] However, this stabilizing influence is sensitive to the form of the unperturbed hot electron distribution function. Numerical results using two different unperturbed hot electron distribution functions will be presented.

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*Work supported by the U. S. Department of Energy under Contract No. DE-AC03-76-ET-53057.

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DYNAMIC COUPLING OF THE PLASMA, SHELL, COILS, AND IRON IN ZT-40M*

R. W. Moses
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

If a Reversed-Field Pinch (RFP) were surrounded by a perfectly conducting shell, image currents in the shell would compensate for coil imperfections and forbid plasma modes that have magnetic flux penetrating the shell. The 2 cm thick aluminum shell on ZT-40M acts like a perfect conductor on short time scales, but in 2-3 ms the plasma is coupled to the coils and to the iron causing plasma drift and instability, respectively. Plasma drift is compensated by a vertical field trim coil that makes up the difference between the vertical field provided by the transformer and that needed by the plasma, a 2-3% correction. The plasma-shell-iron instabilities are $m = 1$, $n = 0, 1, 2...$modes. Analytic time constants have been derived for instabilities due to the segmented shell of ZT-40M. Eigenmodes with horizontal motion have an e-folding time $\tau_h \simeq 32$ ms. Toroidal gaps in the segmented shell cause it to be less effective for stabilizing vertical modes, making $\tau_v \sim 0.95\ \tau_h$. These instabilities will grow faster near the poloidal gap because the $m = 1$ component of the shell current is interrupted there. The e-folding time may be as low as $\tau \sim 10$ ms. Although these instabilities are slow growing, they may gradually change the equilibrium fields to a configuration that is unstable for fast MHD modes. Indeed the lifetime of ZT-40M discharges, 7-10 ms, is comparable to the e-folding times seen here. Experiments are underway to test this theory; if it is correct the instabilities could be compensated by a feedback control system.

*Work performed under the auspices of the USDOE.

ORAL PRESENTATION REQUESTED

CURRENT GRADIENT DRIVEN LOW FREQUENCY ELECTROSTATIC MODES*

R. Farengo, Y. C. Lee, and P. N. Guzdar
Laboratory for Plasma and Fusion Energy Studies
University of Maryland
College Park, Maryland 20742

The problem of current penetration in tokamaks has been a topic of interest for many years. Current gradient-driven instabilities have been considered a likely candidate for providing the anomalous resistivity for rapid current penetration. We have investigated two models for a study of this instability. In one model taking ion temperature to be zero, we have derived a differential equation for the mode structrue of this mode. Numerical and analytical studies of this equation show the existence of a low-frequency mode destabilized by the current gradient. However, sharp gradients in current are required to destabilize the mode. In the second model we have derived an integral equation for finite ion temperature. The integral equation allows for taking into account finite gyroradius, kinetic ion effects, as well as strong current gradients. Detailed numerical results for the solution of the integral equation will be reported.

*Work supported by Department of Energy.

Poster

Kinetic Theory of Stability in EBT with Hot Electron Annulus

S. Z. Zhao* and Young-ping Pao
Courant Institute of Mathematical Sciences
New York University

ABSTRACT

A kinetic theory normal mode analysis is carried out for a straight bumpy cylinder. We look for modes whose growth rates are comparable to the hot electron drift frequency and ion gyrofrequency. The resultant equations contain Fredholm integral equations along field lines as well as partial differential equations and the hot electron response is represented by the drift terms. The final system of equations are used to derive an interchange stability condition and ballooning-type modes with high mode number are also studied.

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*Permanent Address: Harbin Institute of Technology, Harbin, China

UNIVERSAL MODE STABILITY FROM THE THEORY OF THE TWO-POINT CORRELATION

P. Terry and P.H. Diamond
Institute for Fusion Studies
University of Texas
Austin, Texas 78712

The nonlinear stability of the universal mode in a sheared slab is re-examined in the context of a theory for the two point correlation.[1,2] The two-point correlation function satisfies an equation derived from a gyro-averaged drift kinetic equation for electrons and driven by the full electron source with coherent and incoherent contributions to the fluctuating phase space density. The two-point equation is solved approximately and used to obtain the incoherent correlation function equation. We reconsider the question of the stability of the turbulent state by computing the clump-driven enhancement of growth rate[3] for several model radial eigenfunctions. Also considered are the incoherent potential spectrum and its frequency linewidth. To complete the picture, the two-point theory for ions is also formulated and developed. Its role in the problem is discussed.

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Poster Session

1C25

HIGH BETA STABILITY OF IDEAL MHD FIXED BOUNDARY MODES*

G.B. Crew and J.J. Ramos
Massachusetts Institute of Technology, Cambridge, MA, 02139

An analytic flux conserving equilibrium model is used to investigate the stability of finite beta toroidal plasmas against ideal MHD fixed boundary modes. We consider large toroidal wave number localized interchange and ballooning modes as well as small toroidal wave number internal kinks. A practical stability criterion is adopted in order to disregard instabilities localized within a small neighborhood of the magnetic axis, which are physically insignificant.

A parameter space search shows that the internal kink modes reach their high beta stable domain for beta values comparable to those of the ballooning second stability region. This suggests that high-β, low-q stable states may be reached from initial low-β, high-q ones, through a rapid flux conserving heating accompanied by a much slower dissipative relaxation of the q profile.

*Work supported by the United States Department of Energy.

1C26

FORMATION STUDIES OF FIELD-REVERSED CONFIGURATIONS: SPONTANEOUS B TOROIDAL?*

D. W. Hewett
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

The details of the reconnection process at the ends of Field-Reversed Theta-Pinch (FRTP) experiments can greatly effect the properties of the quasisteady configuration that results. The elongation, radial separatrix position, and spindle cusp shape are all strongly dependent on the trapped magnetic flux, which in turn depends on the reconnection rate at the ends. The reconnection process has been studied via hybrid simulation[1] with a variety of physics models. Aperiodic studies with Particle-In-Cell (PIC) ions, zero-mass-fluid electron, and the Hall effect produce internal separatrices (making the field-reversed configuration appear as a series of current rings)[2] and indicate the spontaneous generation of a strong toroidal magnetic field (B_θ) near the ends of the FRC. Representing the ions with a finite-mass fluid, rather than with particles, substantially reduced the generation of internal separatrices but still indicated significant B_θ generation. Turning off the Hall term with fluid ions eliminated both the B_θ and the internal separatrices. PIC ions without the Hall term were similarly uninteresting. Finite resistivity as well as finite electron conductivity do not appear to be important in the generation at the B_θ. Results and further details will be presented. This work suggests the Hall term is not only too large to be ignored but essential in properly representing the B_θ, which develops during the formation of FRCs.

1. D. W. Hewett, J. Comp. Phys. 32, 378 (1980).

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*This work performed under the auspices of the USDOE.

NUMERICAL CALCULATION OF ICRF FIELDS IN EBT DEVICES*

C. W. Nestor† and D. B. Batchelor
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

H. Weitzner
New York University
New York, New York 10012

Ion cylcotron heating experiments are being conducted on EBT-S and are expected to play a major role in EBT-P. Knowledge of the R-F field patterns excited by the antenna is a prerequisite for calculation of plasma heating rates and distribution function modification. We have therefore begun development of a computer code to calculate the wave fields in realistic EBT geometry using a variational principle. A bumpy cylinder plasma equilibrium is used in which the magnetic field and density vary in r and z but are rotationally symmetric about the z axis. The plasma currents are described by the cold plasma conductivity. The boundary is modeled as a sequence of perfectly conducting cylinder segments of alternating large and small radius. Effects of toroidicity are included by imposing periodic boundary conditions at the ends of the N sector bumpy cylinder. Also, a method has been developed to reduce the N cavity problem with one driven cavity to a sequence of N one cavity problems.

The present version of our program is designed to use sparse-matrix subroutines[1] to solve the linear equations for the field components; this requires storing only the indices and values of the non-zero matrix elements. For a sample problem with 6 field components per node, 69 nodes, and 52 elements, we need ∿2700 words of storage for the sparse-matrix method, as compared to ∿170,000 words for the full matrix. Calculation and storage of the non-zero elements and indices for the sample problem required 10 sec of Cray-1 cpu time.

*Research sponsored by the Office of Fusion Energy (OER), U.S. Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

†UCCND Computer Sciences, Oak Ridge, Tennessee.

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Transport Minimizing Equilibria for Tandem Mirrors*

J. R. Myra, D. A. D'Ippolito, and Peter J. Catto

Science Applications, Inc.
Plasma Research Institute
934 Pearl Street
Boulder, Colorado 80302

In order to reduce neoclassical and direct radial losses in tandem mirrors it is desirable to construct vacuum magnetic fields for which the particle drift surfaces remain close to the flux surfaces throughout the device. Working with a paraxial vacuum field model, we define a figure of merit, $\mathscr{S} \geq 0$, which bounds the bounce-averaged particle drift normal to the flux surfaces. By performing a functional minimization of $\mathscr{S}$ with respect to the magnetic field profiles, a differential "transport minimizing" equation for the optimum profile shapes is obtained. The procedure may be employed to calculate the optimum fanning, $f(s)$, and/or magnetic field $|B(s)|$ (where s is distance along a field line), subject to a variety of constraints and boundary conditions. Locally omnigenous fields[1] provide the absolute minimum $\mathscr{S} = 0$, and are thus always a special subset of solutions to the transport minimizing equation. The neoclassical diffusion coefficients scale roughly with $\mathscr{S}$ so that its value can be used for comparing the confinement properties of different profiles. As a sample application, we consider the optimization of the transition fields joining an axisymmetric region to a given quadrupole plug. In some situations, it is found that $\mathscr{S}$ can be reduced by an order of magnitude or more by employing the transport minimizing profiles.

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*Work supported by the U. S. Department of Energy under contract DE-AC03-76-ET-53057.

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Modeling of the ZT-40 RFP Experiment

K. A. Werley and G. H. Miley
Fusion Studies Laboratory
Univeristy of Illinois
214 Nuclear Engineering Laboratory
103 S. Goodwin Avenue
Urbana, Illinois 61801

ZT-40, located at Los Alamos, is a key experiment for study of the Reversed-Field Pinch (RFP) concept. Recent results with a metal liner have been encouraging but have some unexplained density, temperature and field dependencies. The goal of the present work is to reproduce ZT-40 (R = 1.14m, a = 0.2m, I_p = 180-200kA) results using a transport code and freely chosen transport coefficients. Such initial modeling helps identify the important physical phenomena which must be included for a good plasma description.(1) These results will be discussed here. Once the important non-transport effects are included, the code can be used to study different transport scaling laws and to provide insight into scaling requirements.

Our approach is to modify RFPBRN(2), an existing 1-D, Lagrangian, MHD RFP transport code, to operate in the convective frame ($\vec{E} \times \vec{B} = 0$). This allows an explicit description of particle diffusion and a natural application of ZT-40 boundary conditions. We choose factor-times-Bohm thermal and particle diffusion coefficients, where the factors are picked to match ZT-40 confinement times. We then add different non-transport physical effects to the code in an effort to reproduce unique phenomena such as the decrease in the particle pumpout rate at late times.

This study has identified several important features of ZT-40 behavior which should be considered in any future RFP transport, next-step experiment, or reactor studies. These features include (1) neutral reflux and its effect on particle pumpout and (2) a significant perpendicular wall electric field ($E_\perp \sim 10$ V/m) which would raise the toroidal plasma current I_ϕ by ~ 70% if $\eta_\parallel$ was classical. Also, (3) an anomalous $\eta_\parallel$ (~ .5 to $10\eta_{\parallel\,class}$) which increases with time is needed in conjunction with (2) to explain the observed negative curvature of the I_ϕ vs. time results.

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LARGE SCALE PARTICLE SIMULATIONS IN A VIRTUAL MEMORY COMPUTER

P.C. Gray, Geophysical Institute, University of Alaska
and
J.S. Wagner, T. Tajima, Institute for Fusion Studies
University of Texas

We envision three methods of approaching more realistic plasma simulations. First we need to increase the minimum timestep $\Delta t(> \omega_{pe}^{-1})$ through the use of implicit schemes, guiding centers, etc. Secondly we need to describe larger distances across each grid $\Delta(> \lambda_{De})$ by using higher order interpolations and splines. Finally we need to describe large system sizes efficiently, which is the subject of this paper.

We have studied the use of Virtual Memory computers such as the VAX-11/780 on large system sizes. Virtual Memory computers can handle very large simulations (> 8M words) by automatically mapping the required address space onto a combination of fast and slow (disc) memory. We find that by periodically applying a sorting algorithm to keep physically adjacent particles near particles with neighboring array indexes, efficiency is improved. The optimum efficiency occurs when the sorting partition equals the page cluster size. Memory is paged in and out of fast memory in clusters of pages (~ 4K words). A one dimensional electrostatic particle code with 32K grids and 20 particles per cell executes 5 times faster when sorted. The sorting time is small compared to the sorted execution time savings. We also present results for 2-D electrostatic and electromagnetic simulations which show similar speed enhancements.

This research supported by DOE Grants DE-8T06-76ER-7005(Univ. of Alaska), DE-FG05-80ET-53088 and NSF ATM81-10539 (University of Texas).

DO DISTORTIONS OF THE BULK IONS FROM MAXWELLIANS AFFECT FUSION REACTIVITY IN TFTR?*

A. A. Mirin and G. P. Tomaschke
National Magnetic Fusion Energy Computer Center
Lawrence Livermore National Laboratory
Livermore, California

It has been shown that during the heating of a warm background ion species by a more energetic ion species, the warm ion distribution function departs from that of a maxwellian[1]. It has also been shown that the velocity dependence of the particle and energy loss mechanisms is a crucial factor in determining the manner in which the bulk ions deviate from maxwellians[2]. This study addresses the question of the extent to which these distortions cause an enhanced fusion reactivity in a TFTR-like plasma.

Two scenarios are considered. In Scenario I, Fokker-Planck equations for the distribution functions of the bulk deuterons and tritons are solved, subject to one of several velocity dependent energy loss mechanisms. The distribution functions of the hot injected deuterons and of the fusion alpha particles are computed according to Ref. 1, and the electron temperature and the densities of all of the charged species present are chosen according to Ref. 3; these quantities are all assumed to be fixed.

Scenario II is like Scenario I, except that the warm deuterons and tritons are taken to be maxwellian, and their temperatures are determined by solving rate equations.

Fusion reactivities for the two scenarios are compared.

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Would prefer Poster Session.

CALCULATION OF SELF-CONSISTENT RADIAL ELECTRIC FIELDS IN TANDEM MIRRORS*

S. P. Auerbach, R. H. Cohen, J. M. Gilmore,
A. A. Mirin, L. D. Pearlstein, and M. E. Rensink
Lawrence Livermore National Laboratory, University of California
Livermore, California 94550

ABSTRACT

In the central cell of a tandem mirror the radial electric field is determined by competition between non-ambipolar radial transport and axial loss. Equating total ion loss from a flux tube (radial plus axial) to the total electron loss yields the radial charge balance equation (RCBE), which is a nonlinear 2nd order ODE for the potential. The RCBE depends nonlinearly on both the electric field and the potential. This nonlinearity leads to moving singularities (jumps in the radial electric field) whose position and magnitude depend on boundary conditions. The RCBE is solved subject to the boundary condition that the outermost singularity (at which the radial electric field is zero) must occur at or beyond the plasma edge.

Two different methods for solving the RCBE have been implemented: a vector Newton's method, and a shooting method. When the Newton's method fails, the shooting code indicates that the failure is due to a singularity whose position and type is incompatible with the boundary conditions.

A sequence of code simulations in which the functional form of the resonant transport coefficients is scaled up by successive orders of magnitude indicates that quenching of radial transport occurs, due to flattening of the radial potential profile. This is in accord with previous predictions.[1]

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NUMERICAL SIMULATION OF THE BOOTSTRAP CURRENT

J. L. Shohet
Torsatron/Stellarator Laboratory
The University of Wisconsin
Madison, Wisconsin 53706

The bootstrap current, which has been predicted to appear in many toroidal magnetic devices, has not been seen experimentally. In tokamak devices, the presence of the large ohmic current may easily mask the presence of the bootstrap current, and thus the most appropriate configuration used to search for the bootstrap current has been a net-current-free stellarator type. (1)

The bootstrap current should result in a net toroidal current, driven essentially by the density gradient in trapped particle orbits.(2) An attempt to simulate the bootstrap current by looking at a 2-1/2 dimensional particle-in-cell simulation has been made. The basic configuration used for this study was a poloidal annular section of a torus, which was "unwrapped" so as to be in rectangular coordinates. The horizontal axis represents the minor radial coordinate, and the vertical axis represents the poloidal coordinate, and is periodic.

20,000 simulation particles were placed in this region and the equation of motion solved for all three components of velocity, but only for 2 components of position. Components of a d.c. magnetic field in both toroidal and poloidal directions varied across the region so as to produce a tokamak-like magnetic field without the need for plasma current. Both trapped and circulating particles could be observed. A fully self-consistent Poisson algorithim was used to obtain the electric and magnetic fields of the individual particles which were superimposed on the external fields. A density gradient in the minor radial direction was set up as an initial condition.

Periodic boundary conditions at the outside of the "torus" and reflecting boundary conditions on the inside of the torus were imposed. The net z-directed velocity (toroidal velocity) of the electrons and ions was calculated after each time step (10% of the electron cyclotron period), which should give evidence of the bootstrap current. A small net electron toroidal current is seen to appear. It reaches a steady state roughly after 2,500 cyclotron periods. The steady state value of the current does not change with poloidal field, perhaps because the bounce frequency and the poloidal radius of gyration change oppositely as the poloidal field is varied. As density is increased, the current is seen to drop. Additional parametric studies are continuing.

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1C34

Equilibrium and Stability of Configurations with Spatial Magnetic Axis

H. Weitzner and M. Mond

Courant Institute of Mathematical Sciences
New York University

ABSTRACT

We consider two types of configurations whose magnetic axes are three dimensional curves. The first case includes systems such as figure eight and snake whose rotational transform arises from geometry. In the second case we treat systems with applied helical fields.

We set up a formalism to treat equilibria with nonplanar magnetic axes. Unlike the standard expansions about the magnetic axis, our formalism gives the equilibrium out to a boundary wall or to the outer coils. The expansion is in low inverse aspect ratio and low β.

In the first case we examine two different scaling assumptions. The first assumes that β is proportional to the square of the inverse aspect ratio while according to the second β is proportional to the inverse aspect ratio. In the latter, "high β" case, stable configurations can be found provided the pressure profile is flat enough near the magnetic axis. In the second case, with applied helical fields, we take a large number of periods of straight stellarator and bend it into a torus. In this case β is proportional to the inverse aspect ratio, and the stability properties are the same as those of straight systems; i.e., as we have shown previously, there exist low shear stable equilibria.

Poster Session preferred.

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1C35

Resonant Ion Transport in EBT*

J. S. Tolliver**, D. E. Hastings, E. F. Jaeger and C. L. Hedrick
Oak Ridge National Laboratory, Oak Ridge, Tennessee

Abstract

We use a model of Spong and Hedrick and their associated variational principle and show that it applies for both banana and plateau ions in EBT. We derive the perturbed distribution function in the banana regime including the Weiner-Hopf boundary layer correction. We then use the plateau and banana results to obtain a continuous approximation to the energy dependent flux. We use this approximation to obtain analytic formulae for the particle and energy diffusion coefficients both for zero and non-zero poloidal electric fields. These formulae can be written in terms of special functions and reduce to all the familiar limits. These coefficients can be incorporated into transport codes for EBT.

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*Research sponsored by the Office of Fusion Energy, Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

**UCCND Computer Sciences, Oak Ridge, Tennessee.

[1] D. A Spong and C. L. Hedrick, Phys. Fluids 23, 1903 (1980).

This abstract to follow "EBT Transport and Orbits for Pedestrians."

Model Equations for Coupled Drift and Shear-Alfvén Turbulence*

P. K. Kaw
Plasma Physics Laboratory, Princeton University
Princeton, N.J. 08544

It is well-known that in a finite $\beta(\gtrsim m_e/m_i)$ magnetically confined plasma, there is a linear coupling of drift waves and shear-Alfvén waves. In this paper, the nonlinear fluid equations describing the dynamics of finite amplitude drift and shear-Alfvén waves (with a model term mocking up curvature effects) have been reduced to three evolution equations for the density n and the scalar and vector potential fluctuations ϕ and $A_{\parallel}$. The dominant nonlinear effects are (i) $E \times B$ convection of the ion fluid and (ii) parallel flow of electron fluid along bent field lines. Relationship of these equations with ideal MHD turbulence is discussed. Next, we discuss various limits in which the equations reduce to a two-dimensional problem. These include the electrostatic Hasegawa-Mima limit, a large $\tilde{b}$ limit, a resistive drift-Alfvén instabiity limit, a strong curvature instability limit etc. It is suggested that these equations with appropriate sources and sinks could be used to investigate the strong fluid turbulence of drift waves, shear Alfvén-waves and a model for high m, n ballooning modes.

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Poster Session

POSTER SESSION

ANOMALOUS FAST ION DIFFUSION DUE TO MAGNETIC FIELD FLUCTUATIONS*

R. W. Harvey, D. K. Bhadra, T. Yamagishi, and R. L. Miller
General Atomic Company
San Diego, California

ABSTRACT

In neutral beam experiments, the observed improvement of energy confinement with plasma current may be due to finite banana width effects which, in conjunction with magnetic fluctuations, result in the loss of fast ions before they heat the background plasma. We consider and compare two models for anomalous fast ion diffusion: (1) Stochastic magnetic field fluctations with $k_{\perp}\rho_{Li} \sim 1$ result in pitch angle scattering via a finite Larmor radius effect.[1] Initially contained orbits are thereby scattered into unconfined orbits. Approximate estimates show that $\delta B_r/B$ must be 10^{-3} for this mechanism to give significant fast ion losses. (2) We next consider the orbits of fast ions in a tokamak magnetic field with m=1 and 2 island structures superposed. The resultant fast ion losses are computed using a guiding center orbit code including simulation of Coulomb collision effects by the Monte Carlo technique.

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*Work supported by Department of Energy Contract DE-AT03-76ET51011

Current Driven Resistive MHD-Instabilities in Axisymmetric Toroidal Systems*

J. Manickam, R. C. Grimm, and R. L. Dewar
Plasma Physics Laboratory, Princeton University
Princeton, N.J. 08544

Resistive MHD modes in toroidal geometry can be studied computationally using the PEST 3 code, which treats the problem as a boundary layer calculation[1]. In this formulation we first compute the 2D ideal MHD solutions (with particular concern to a proper treatment of the singular behavior) in the external regions between singular surfaces, and then the resistive solution in the inner boundary layers. Asymptotically matching the solutions results in a dispersion relation which can be solved to find the eigenvalues of the unstable modes. We report results obtained for zero pressure, finite aspect ratio, general cross-section tokamak equilibria where we allow only one rational surface to have finite conductivity. We study the dependence on aspect-ratio, ellipticity and current profile. With fixed q profile, decreasing the aspect ratio can stabilize the mode as does increasing the non-circularity. The current gradient (J') at the rational surface plays a key role. Stability is improved by reducing the magnitude of J' at the singular surface. Finally, we present preliminary calculations of the growth rate obtained after carrying out the matching for the case of several resistive layers.

*This work was supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

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Poster Session

1C39

ANALYTICAL AND NUMERICAL CALCULATIONS OF NONADIABATICITY IN EBT GEOMETRY*

S. Hamasaki, N. A. Krall, and J. L. Sperling
JAYCOR
San Diego, California 92138

We have evaluated the analytic expressions for the nonadiabatic jumps in the magnetic moment, μ, appropriate to the bumpy-cylinder, magnetic field geometry. These analytic expressions have been verified numerically by following the exact orbits of charged particles in the assumed magnetic field geometry. We have included the formulas for the nonadiabatic jumps in our electron ring model in order to study their role in the ring energy balance. Our studies show that the nonadiabaticity reduces the parallel electron ring temperature but barely affects the perpendicular temperature. Consequently, nonadiabatic effects alone cannot explain the empirical scaling law for the electron ring temperature. However, the combination of the non-adiabaticity and whistler turbulence provides better agreement with the observed scaling.

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Calculation of Stellarator Currents at Low Collisionality*

Harry E. Mynick
University of Wisconsin
Madison, WI 53706

At low collisionality, the plasma distribution function f may be taken to be a function of the invariants (E, μ, J) (energy, gyroaction, and bounce action), where μ and J, written in terms of particle phase space coordinates, have corrections μ_1, J_1, which subtract off oscillatory behavior at the gyro- and bounce frequencies $\Omega_{g,b}$ of the more familiar, lowest-order expressions μ_0, J_0.[1] The current $\underset{\sim}{j}$ has been calculated for a stellarator using this form for f. It arises from the corrections to f at first order in μ_1, J_1. It may be decomposed into a part $\underset{\sim}{j}_g$, due to the terms in μ_1, J_1 oscillatory at Ω_g, plus a part $\underset{\sim}{j}_b$, due to the term in J_1 oscillatory at Ω_b. Both are explicitly evaluable. $\underset{\sim}{j}_g$ yields the diamagnetic current, plus an additional term, needed in order that $0 = \nabla \cdot \underset{\sim}{j}$. $\underset{\sim}{j}_b$ gives the bootstrap current appropriate to a stellarator. It is approximately equal to the sum of a toroidally-symmetric and a helically-symmetric part $\underset{\sim}{j}_t$ and $\underset{\sim}{j}_h$, where

$$\underset{\sim}{j}_{t,h} \simeq -\hat{b}\,(3c/2B)(dp/dr)[\varepsilon_{t,h}^{1/2} a_{t,h}] \, .$$

The geometric factors $a_{t,h} \equiv (\hat{r} \cdot \nabla\theta_{t,h} \times \underset{\sim}{B})/(\underset{\sim}{\nabla}\theta_{t,h} \cdot \underset{\sim}{B})$ typically have opposite sign, so $\underset{\sim}{j}_b$ can vanish for some ratio $\varepsilon_t/\varepsilon_h$ of the toroidal to helical ripple amplitudes.

*Work supported by the U. S. DOE under Contract No. DE-AS-02-78ET52048 and Contract No. DE-AS02-78ET53082

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ION HEATING BY RF WAVES IN A BUMPY TORUS*

J. L. Sperling, S. Hamasaki, and N. A. Krall
JAYCOR
San Diego, California 92138

Using a hybrid fluid-kinetic approach, which includes the effects of quasilinear heating, coulomb collisions, charge exchange, and neoclassical transport, ion bulk and tail temperatures are calculated for rf heated plasmas in a bumpy torus. It is demonstrated, assuming neoclassical ion transport, that spatial loss is the dominant factor which limits ion temperatures in EBT-S. Although charge exchange is predicted to contribute more to the overall power balance in EBT-P than in EBT-S, transport is also still expected to restrict ion temperatures in EBT-P. In both EBT-S and EBT-P, it is shown that heating of the majority ion species by the minority ion species is not efficient because collisional coupling between the two ion species is weak. This result holds even for applied frequencies which directly heat the minority ion species at the first harmonic ion-cyclotron resonance.

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Conditions for the Attainment of the Minimum-Energy State of a Diffuse Pinch Discharge

M.G. Rusbridge

Department of Pure and Applied Physics,
UMIST,
Sackville Street,
Manchester M60 1QD.
U.K.

Abstract

It has been shown that subject to suitable constraints, the minimum-energy state of a diffuse pinch discharge is that in which the magnetic field configuration is described by the Bessel Function Model (BFM). The detailed structure of this state is discussed and it is proposed that it is a limiting case of the Tangled Discharge Model (TDM) [1]. The essential features of this structure are that there is only one line of force which ergodically fills the entire discharge volume, and that transverse currents vanish identically so that current exactly follows the single line of force, leading to the condition that (current density) $\propto$ (magnetic flux density), i.e., $j_{\parallel} \propto B$, everywhere. The BFM follows immediately from the condition.

It is shown that the vanishing of the transverse current is only plausible in the limit of infinite conductivity. With finite conductivity, random transverse currents associated with turbulence flow, and these destroy the unique relationship between j and B and hence prevent the formation of the BFM in principle. In practice, it is sufficient that the conductivity be greater than a critical value, which can be expressed in terms of the magnetic Reynolds' number S. In conditions similar to those in ZETA, the requirement is

$$S \gg S_c = R^3 \Lambda^{3/2} \Delta^{-9/2}$$

where R is the discharge radius, and Λ and Δ are the parallel and perpendicular scale lengths of the turbulence.

In ZETA, $S_c \simeq 3\times10^4$, and it is shown that there is experimental evidence consistent with the conclusion that the BFM is attained only when $S \gg S_c$.

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TWO DIMENSIONAL SOLITARY DRIFT WAVE WITH MAGNETIC SHEAR AND ELECTRON KINETICS

J.D. Meiss and W. Horton, Jr.
Institute for Fusion Studies
University of Texas
Austin, Texas 78712

The equations obtained from cold fluid ions with adiabatic electrons are a coupled pair for electrostatic potential and parallel ion velocity. When $k_{\|} \to 0$ these reduce to the Charney equation of geophysics which is known to have solitary vortex solutions.[1] We show that if $k_{\|} \neq 0$ solitary vorticies propagating at any angle in the y-z plane are obtained. The velocities of these vorticies complement the phase velocities of linear drift-Alfvén modes. In the presence of magnetic shear a solitary vortex centered on a rational surface radiates energy. If the vortex radius is smaller than the Pearlstein-Berk turning point, then the energy is radiated slowly when $c > V_{de}(1 + L_n/L_s)$ or $c < 0$ where c is the vortex speed. Non-adiabatic electron effects are included by using the linear form of the response. In contrast to the linear modes, solitary vortices are damped by these effects. Some simulations with a one-dimensional model are presented.

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Poster Session

Numerical Simulation on Electron Cyclotron Resonance Heating

H. Okuda and H. Abe*

Plasma Physics Laboratory, Princeton University, Princeton, NJ 08544

One-dimensional electromagnetic relativistic particle simulations have been carried out to study the wave propagation and electron heating associated with the upper-hybrid mode conversion in an inhomogeneous, magnetic field.[1] An extraordinary mode launched at the high magnetic field side propagates toward the upper-hybrid resonance layer. After suffering a small but finite attenuation at the electron cyclotron layer causing modest electron heating, the pump wave is mode-converted to short wavelength, large amplitude electrostatic waves at the upper-hybrid layer.

Large electron heating is observed at the cyclotron layer when the electrostatic waves propagate toward the high field side and reach the cyclotron layer. The propagation speed is roughly of the order of electron thermal speed. For a sufficiently large pump, heating near the upper-hybrid resonance is large owing to their large electrostatic field.

When the mode-converted electrostatic waves reach the cyclotron layer, the plasma starts emitting electromagnetic radiation into vacuum region whose pointing power is as much as that of pump wave. The observed density fluctuations associated with the mode-converted electrostatic waves may be important for the reflection of pump wave. Simulation results will be presented for different pump amplitude.

*permanent address: Department of Electronics, Kyoto University, Kyoto, Japan.

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MHD Stability Limit and Growth Rates in Straight Stellarators with Strong Shear

P. Merkel, J. Nührenberg and W. Schneider
Max-Planck-Institut für Plasmaphysik, EURATOM-Association, D-8046 Garching

R. Gruber, F. Troyon
EURATOM-Switzerland Fusion Association, Centre de Recherche en Physique des Plasmas, Ecole Polytechnique Fédérale de Lausanne, CH-1007 Lausanne

A helical equilibrium and ballooning stability code [1] and the HERA code [2, 3] are applied to a class of equilibria which may be characterized as straight analogues of the HELIOTRON [4]. The rotational transform per helical period on axis and at the edge are $\iota_o = 0.052$ and $\iota_E = 0.211$, respectively; the helical aspect ratio is $L_p/2\pi a_p \sim .7$. The pressure profile is approximately $\beta_o(1-(\rho/a_p)^4)$, so that instability at the centre is avoided. The second arbitrary equilibrium function and the pressure profile are adjusted in detail such that the net longitudinal current vanishes to good approximation; then the plasma boundary is independent of β to good approximation for the range of β's considered $0 \le \langle\beta\rangle \le 0.06$. Flux surfaces and ι are shown in Fig.1 and 2. The ballooning stability limit occurs at $\langle\beta\rangle \approx 0.005$. Growth rates of internal modes have been obtained. The growth rate of the m = 1 mode (2m - poloidal node number) is plotted in Fig.3 and shows approximately linear dependence on β. The marginal point obtained by formal extrapolation occurs at $\langle\beta\rangle \sim 0.01$ and growth rates are substantial for $\langle\beta\rangle = 0.05$. Details of the mode structure as well as results for external modes will be presented.

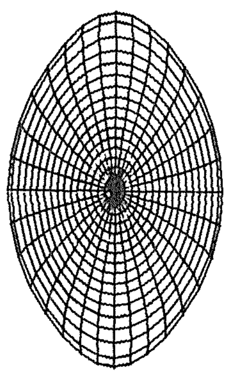

Fig.1

Acknowledgements

We would like to thank Miss R. Grossmann for carrying out part of the numerical calculations.

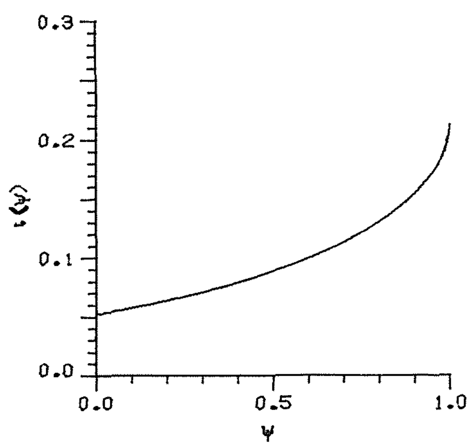

Fig.2

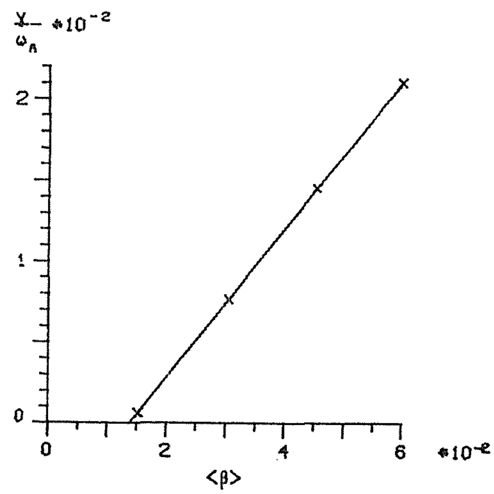

Fig.3

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THREE-DIMENSIONAL MHD PARTICLE CODE FOR HIGH-BETA TOKAMAK SIMULATION

F. Brunel and T. Tajima
Institute for Fusion Studies
The University of Texas at Austin
Austin, Texas 78712

A full dynamics MHD code is necessary for a better understanding of tokamak behavior in high-beta regimes where pressure-driven modes play an important role. Our MHD particle code[1] using the Lax-Wendroff scheme to integrate the magnetic field has been extended to three dimensions with conducting boundaries to simulate a tokamak in cylindrical geometry. In the $2\frac{1}{2}$-D case (two spatial dimensions and three velocities), due to the non-diffusive Lax-Wendroff scheme coupled with the particle description of the fluid which satisfies exactly the continuity equation, the code can handle strong density gradient and can describe the ideal ballooning mode[1] in a natural way without using artificial viscosity terms. The code can also describe the fast reconnection regime when a sharp current sheet appears. In such a case we learned that plasma compressibility plays an important role for faster reconnections.[2]

Preliminary results in 3-D will be presented in the low beta and high aspect ratio limit and compared to the reduced MHD model.

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Poster Session

Instabilities Driven by the Parallel Variation of the Electrostatic Potential in Tandems*

R. E. Aamodt, X. S. Lee, and P. J. Catto

Science Applications, Inc.
Plasma Research Institute
934 Pearl Street
Boulder, Colorado 80302

Studies of low frequency instabilities in tandem mirrors normally treat the $\underset{\sim}{E} \times \underset{\sim}{B}$ drift frequency as a constant along the magnetic field line $\underset{\sim}{B}$. However, this may become inappropriate in the end sections where substantial electrostatic potential changes are crucial to the axial confinement and economical operation of such devices. In general the diamagnetic and gradient-B drifts may vary rapidly along $\underset{\sim}{B}$ in these sections as well. It is demonstrated that the shear induced by the parallel variation of the plasma drift can provide a destabilizing influence.

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1D4

Simulation of Current Drive with Lower Hybrid Waves*

V. K. Decyk, J. M. Dawson, and G. J. Morales
Department of Physics, University of California
Los Angeles, California 90024 U.S.A.

A computer simulation study of current drive with lower hybrid waves has recently been undertaken, using an electrostatic particle code. The antenna consists of four capacitor plates, phased ninety degrees apart, to model a phased waveguide array. The simulations examine the dynamics of current generation for a given initial velocity distribution, such as a "slideaway" distribution. The evolution of the velocity distribution and the corresponding current profile in space will be shown for a number of cases.

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SIMULATION OF IRON TRANSPORT IN COUNTER-INJECTED ISX-B PLASMAS*

E. C. Crume and D. E. Arnurius

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Using the impurity transport simulation code IMPTAR, we have simulated experimental observations[1] of iron radiation from counter-injected ISX-B plasmas. The IMPTAR code implements the recent neoclassical impurity transport theory of the review of Hirshman and Sigmar,[2] but, as a matter of practicality, also has provisions for adjusting transport coefficients in an ad hoc manner. Because of the usual oxygen contaminant, both oxygen[3] and iron atomic physics were required, and the RECYCL code was employed to investigate appropriate modifications in the atomic rate coefficients.[1]

In order to reproduce the observed time histories of the iron radiation it was necessary to continually increase the rate of inward transport from about the time the beam turns on until shortly before the (soft) disruption occurs which destroys the plasma. This is qualitatively in agreement with recent theories[4,5] which predict beam-enhancement of transport. We plan to implement forms of these theories in IMPTAR at the sophistication level of Ref. 2 soon; see, in this regard, the results of Sigmar and Howe.[6]

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*Research sponsored by the Office of Fusion Energy OER, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

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Beam and Alpha-Particle Effects on Tokamak Microinstabilities*

G. Rewoldt and W. M. Tang
Plasma Physics Laboratory, Princeton University
Princeton, N.J. 08544

In comprehensive previous studies of general (numerically computed) MHD equilibria, it was established that low-frequency microinstabilities should be present in realistic tokamak plasmas.[1] Since these modes remain a plausible contributing cause for the observed anomalous transport, it is important to determine the influence of energetic beam and alpha particles on their stability. To do this it is necessary to represent the beam-ion-species and the fast alpha particles with equilibrium distribution functions which are arbitrary functions of energy and pitch angle. These calculations have been carried out for cases corresponding to the PLT and PDX experiments with parallel and perpendicular neutral beam injection respectively. It is found that the replacement of background ions by either beam ions or alpha particles has a stabilizing effect on the familiar trapped-electron-drift-type modes. Reasons for this trend and its implications will be discussed, and results from the analysis of a sequence of PLT equilibria with increasing beam power will also be presented.

*This work was supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

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Poster Session

Simulations of the Toroidal Cusp Experiment*

J. M. Dawson, J. N. Leboeuf, N. C. Luhmann, Jr.,
S. T. Ratliff, and M. Rhodes
University of California, Los Angeles

We have performed computer simulations of the Toroidal Cusp Experiment (TCX), a plasma device built and operated at UCLA. TCX is a toroidal MacKenzie machine with an external magnetic field provided by 48 magnetic cusps arranged in poloidal rings. A transformer generates a toroidal electric field which causes a current to flow in the plasma. Experimentally, the following parameters are observed in hydrogen: $n_e = 2 \times 10^{13}/cm^3$, $T_e = 20ev$, $T_i = 40 - 110$ ev. The toroidal current is carried mostly by the ions.

We have developed a computer simulation model of TCX using a 2-1/2D electromagnetic particle code. Basically, the simulation results (the electrons are restrained by the magnetic cusp fields, the ions are free to move, there is ion heating, and a relatively large fraction of the current is ion current) agree with those of the experiment, and are explained by simple physical theoretical arguments. These provide the scaling observed in the simulation model. In the computer simulations, we observe distortion of the current channel, distortion of the pinch magnetic field lines, and approximately, exponential growth of the electrostatic energy.

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STABILITY OF MULTIHELICAL TEARING MODES IN SHAPED TOKAMAKS

W. Kerner and H. Tasso

Max-Planck-Institut für Plasmaphysik, EURATOM-ASSOCIATION
D-8046 Garching, Germany

The stability of multihelical tearing modes in tokamaks with shaped cross-sections is determined numerically. The equilibria with arbitrarily prescribed currents and plasma boundaries are computed with the Garching equilibrium code /1/, and then the mapping into flux coordinates is done with the ERATO /2/ algorithm. The stability analysis is performed by combining the energy principle of Tasso and Virtamo /3/ with the finite element method, leading to a Hermitian eigenvalue problem where the sign of the lowest eigenvalue determines the stability. The method allows inclusion of a large number of singular surfaces. Poloidal and radial couplings are discussed. For a specific D-shaped configuration high poloidal m number modes are found to be unstable. Completely stable profiles were constructed by appropriately smoothing the current distribution.

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Electron Transport in Stellarators*

R. M. Kulsrud and D. Ho
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

Electrons are sufficiently collisional, even in reactors, that their superbanana transport can reliably be estimated from a simple model. This consists of a straight helix with the only toroidal effect included a vertical toroidal drift. This enables us to include a number of transport phenomena: electric field, thermal diffusion, plasma rotation and instabilities. It is found that the electron transport flux is independent of plasma density, so that it is expected that the density will increase until instabilities play a role. Also transport is very sensitive to particle energy so that particle and energy transport is by electrons with energies four or five times thermal. The absolute value of electron heat loss is sufficiently large so as to be of concern for some proposed numbers for stellarator reactors (1 meter minor radius, aspect ratio 10, density $2 \times 10^{14}/cm^3$, B = 5T). One can also evaluate ion loss on the basis of this model and it is found that they are dominated by the electric field, and that their transport is much less energy sensitive. Although the model is not so reliable for ions, it can be concluded in some cases, at least, that the ion heat loss is actually comparable with electron heat loss.

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Oral Session

PRESSURE GRADIENT DRIVEN TOROIDAL DRIFT MODES

W.C. Anderson and W. Horton
Institute for Fusion Studies
University of Texas
Austin, Texas 78712

The theory of pressure gradient driven drift modes localized to the outside of the torus is developed further. For toroidicity $\varepsilon_n = r_n/R$ and ion pressure-to-density gradient $1 + \eta_i$, we report the variations from the electrostatic fluid growth rate $\gamma \sim [2\varepsilon_n(1 + \eta_i)]^{1/2}$ as they arise from the kinetic effects of (1) the FLR Bessel functions, (2) the ∇B-curvature drift resonance, and (3) the even/odd parity of the eigenfunction affecting the electron response.[1,2] To account for finite β and nonlocality, we formulate the electromagnetic mode equations in the poloidal magnetic flux coordinates and the simplified Shafranov coordinates. Weak modifications to the growth rate occur at $\beta \sim \varepsilon_n^2$, and the transformation of the mode from an electrostatic-like polarization to a MHD-like polarization at $(1 + \eta_i)\beta \sim \varepsilon_n/q^2$ is investigated.

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Work supported by DOE Grant No. DE-FG05-80ET-53088.

1D11

THE IMPORTANCE OF POLOIDAL NON-UNIFORMITY AND FINITE ION POLOIDAL GYRO-RADIUS IN TOKAMAK IMPURITY TRANSPORT

A.A. Ware
Fusion Research Center
University of Texas
Austin, Texas 78712

It will be shown that in the neoclassical diffusion of impurity ions (Γ_z), the three previously ignored effects - the poloidal non-uniformity of the Z-ion density $[\tilde{n}_z(\theta)]$, electrostatic trapping and the necessary poloidal rotation for equilibrium ($\bar{V}_\theta$) - all make contributions to Γ_z as great or greater than the usual magnetic trapping terms. For example, for Z-ions moderately in the Pfirsch-Schluter regime, $\Gamma_z = -[2(r/R)\cos\theta + (\tilde{n}_z/n_z)]\tilde{F}_{z\parallel}/ZeB_\theta$, where $\underset{\sim}{F}_z$ is the friction force. Thus the often observed large $(\tilde{n}_z/\bar{n}_z)$ will make an important contribution to Γ_z. Also, in $\tilde{F}_{z\parallel}$ there are extra terms due to electrostatic trapping and a term proportional to $(B/B_\theta)\bar{V}_\theta\tilde{n}_z$ which will often be the most important of all.

In hot ion plasmas (i.e. T_i = 200 eV in I = 60kA or T_i = 5 keV in 400 kA) the lowest order distribution function for the hydrogen ions is highly non-Maxwellian. The original experimental evidence of Goldston[1] was explained by a two-Maxwellian model[2] with the hot ion plasma from the discharge center diffusing out too rapidly to thermalise with the incoming cold plasma. This model, recently confirmed by measurements on PDX[3], leads to further changes in Γ_z.

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Oral Session

TRANSPORT COEFFICIENTS IN WEAKLY TURBULENT PLASMAS

G. Hazak and I. B. Bernstein

Yale University, Applied Physics,
P.O.Box 2159, Yale Sta., New Haven,
Connecticut 06520

ABSTRACT

Two calculations are presented, both aimed towards the development of a reliable technique for evaluating objects such as fluctuating field autocorrelation functions and velocity space diffusion tensors for weakly unstable inhomogeneous plasmas.

In the first calculation we use geometric optics to determine the field of a radiating point source in a nonhomogeneous plasma and to construct the velocity space diffusion tensor for a cold inhomogeneous plasma sphere. In the second part we suggest a representation of the geometric optics solutions by oscilatory integrals. This representation enables us to treat the physical objects mentioned above by a formalism similar to the Fourier integral transform used for homogeneous systems.

1D13

How Flux Surfaces Break Up*

R. S. Mackay
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

Numerical investigation of one parameter families of reversible area preserving maps indicate that flux surfaces with winding number equal to a generalized golden ratio break up in a universal way, governed by universal scalings. As the parameter approaches a critical value, such a surface develops thin spots. Beyond the critical value there remain field lines with the given winding number, but they only fill up a "cantorus", i.e. although they come back arbitrarily close to themselves, the closure of their intersection with a poloidal section has gaps between any two of its points. We also present evidence that generalized golden ratio surfaces are locally the most robust.

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Poster Session

Stability of High Beta Tokamak Spectral Equilibria*

K. M. Ling, S. C. Jardin, and D. A. Monticello
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

Calculations of axisymmetric tokamak plasma equilibria are facilitated by a spectral representation of the Cartesian coordinates, and by a variational principle.[1] Typical of a spectral method, the error decays exponentially as the number of spectral amplitudes increases. For free-boundary equilibria consistent with a set of external current coils, the spectral amplitudes for the plasma-vacuum interface are obtained by minimizing a mean-square error with respect to the amplitudes.[2] Results are applicable in the high beta regime. Stability of both fixed-boundary and free-boundary high beta spectral equilibria are studied by using PEST-II and the BALLOON stability codes.

*This work supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

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Poster Session

TIME-VARYING MAGNETIC PUMPING IN TANDEM MIRRORS*

J. A. Byers, R. H. Cohen, D. E. Baldwin, and P. Poulsen
Lawrence Livermore National Laboratory, University of California
Livermore, California 94550

We have derived a theory, and carried out test particle simulation, for simple models of rf magnetic pumping on both the azimuthal drift and axial-bounce time scales. For drift pumping, we use a simplifed model where $E_\perp/B$ radial drifts result from an m=1 $E_\perp$ field of a coil localized near the inboard mirror of the thermal barrier. This localization aids in selectivity, but it decreases the effective strength of $E_\perp$ by $\tau_{coil}/\tau_{bounce}$. For bounce pumping we induce V_z heating from rf perturbations in B(z) and the consequent change in the ambipolar φ leads to an rf E_z. In either case, a diffusive behavior results if the rf signal is composed of a number of discrete frequencies with the total bandwidth exceeding the expected range of particle orbit frequencies, and if the frequency separation is greater than individual orbital resonance widths. The computer results agree with the theory to within a factor of two. For TMX-Upgrade, comparisons of pumping rates to the fill rates of trapped particles show that the required rf field strengths are much too large. For MFTF-B it may be possible to have a significant effect with $\tilde{B}/B$ in the range of a few percent. In addition, even smaller $\tilde{B}/B$ may be sufficient for pumping impurities. More precise quantitative evaluation awaits resolution of the topic of field penetration into the plasma.

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Numerical Studies of Large k Ballooning Modes in Helical Equilibria

R. Gruber, F. Troyon
EURATOM-Switzerland Fusion Association, Centre de Recherche en Physique des Plasmas, Ecole Polytechnique Fédérale de Lausanne, CH-1007 Lausanne

P. Merkel, J. Nührenberg, W. Schneider
Max-Planck-Institut für Plasmaphysik, EURATOM-Association, D-8046 Garching

The extended version of the HERA code [1] allows a large k mode analysis ($\xi \approx e^{ikz}$) by eliminating the fast poloidal variation of the modes with a suitable phase factor. This method is applied to a class of net longitudinal currentless helical equilibria [2] which was previously studied with respect to low m-number mode stability yielding $\langle\beta\rangle_c = 0.1$ (2m - poloidal node number). The growth rates of the large k, m resonant modes increase with m to a finite limiting value for $m \to \infty$. Preliminary numerical results indicate that the same stability $\langle\beta\rangle_c$ limit is obtained with these modes in accordance with the $m \to \infty$ result obtained from the ballooning stability criterion. In Fig.1 growth rates of an equilibrium with $\langle\beta\rangle = 0.22$ are plotted versus m.

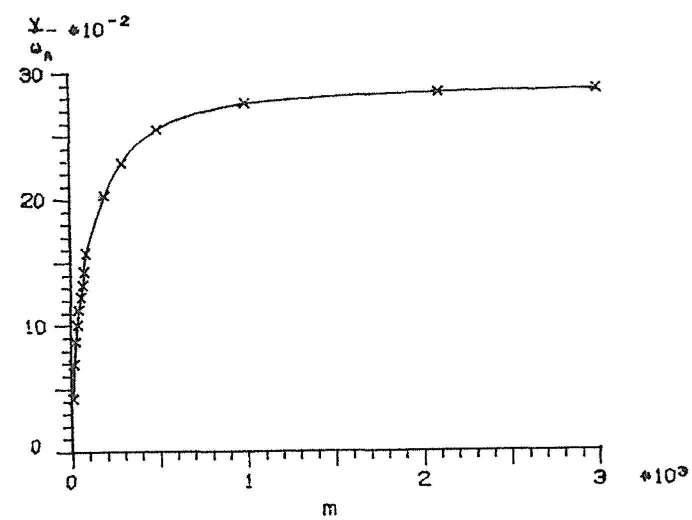

Fig.1

Further studies concern an unstable equilibrium with $\langle\beta\rangle = 0.05$ in which the ballooning unstable region fills only part of the plasma region. The approach to $m \to \infty$ as obtained with the numerically calculated large k mode is being studied.

Acknowledgements

We would like to thank Miss R. Grossmann for carrying out part of the numerical calculations.

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POSTER SESSION

EFFECT OF ICRF ON THE ION TAIL DISTRIBUTION*

S. C. Chiu and C. S. Liu
General Atomic Company
San Diego, California

ABSTRACT

The production of energetic tail ion by ICRF has been confirmed experimentally by PLT, TFR and other groups. In the quasilinear approximation, it can be shown that ICRF produces a tail distribution with an effective temperature $\sim D/\nu_s$, where D is the quasilinear diffusion coefficient and ν_s is the Spitzer slowing down rate. This can have important consequences in ICRF current drive and clamping of neutral beam energy. In the former case, particle trapping poses a limitation to current drive efficiency. In the latter case, ICRF significantly increases the beam particle energy. Analytical estimates of these effects are made. These effects are also numerically studied using a bounce averaged Fokker-Planck code.

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COLLISIONLESS DIFFUSION IN TWO-FREQUENCY ECRH

J.E. Howard, A.J. Lichtenberg, and M.A. Lieberman

University of California, Berkeley

and

R.H. Cohen

Lawrence Livermore Laboratory

Previous calculations modeling two frequency ECRH by a two dimensional area preserving mapping indicated that the addition of the second frequency could raise the adiabatic barrier to stochastic heating by approximately a factor of two in energy.(1) A more complete treatment indicates that, in addition to the above effect, the second resonant frequency raises the dimension of the mapping from two to four. This additional degree of freedom allows diffusion to occur along resonances as well as across overlapping resonances. Previous theory of this "Arnold" diffusion(2) is applied to the two-frequency heating problem. Numerical results from the four dimensional mapping are presented and the implications for particle heating and loss are discussed.

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Evaluation of the MHD Continuous Spectrum*

M. S. Chance, J. M. Greene, and H. Selberg
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

The equations for describing the MHD continuous spectrum are cast in a form which is independent of the coordinate system, but based upon the existence of flux surfaces. Explicit calculation of the spectrum uses a coordinate system appropriate to the physical system under consideration. These equations are solved numerically by, a) direct integration, exploiting Floquet's theorem and the Hamiltonian properties of the equations, and, b) an integral variational method. Both methods are compared. Results are presented for several systems including tokamaks and reversed-field-pinches, showing the effects on the spectrum due to toroidicity, non-circularity, etc.

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Poster Session

SIMULATIONS OF UPPER HYBRID AND ELECTRON CYCLOTRON HEATING*

A. T. Lin and Chih-Chien Lin
Department of Physics
University of California, Los Angeles, CA 90024

A 2-1/2D bounded relativistic electromagnetic particle code is used to simulate upper hybrid and electron cyclotron heating processes by launching obliquely extraordinary waves from the high field side into a plasma with uniform density. At the angle of incident $\theta = 80°$, the waves pass through the cyclotron layer without suffering any significant damping and converts to the backward electrostatic Bernstein wave at the upper hybrid layer. The converted wave propagates back to the electron cyclotron layer and deposits its energy to the electrons. The absorption width can be roughly evaluated by the expression $\Delta x = (\frac{T_e}{mc^2})^{1/2} N_{\parallel} L_m$ which is only a few electron Debye lengths in our case. Initially, the cyclotron absorption is very localized and gradually spreads to the low field side due to the increase of T_e. We then increase the wave amplitude by a factor of two. In this case, the interference of the mode converted Bernstein wave with the incoming wave gives rise to a large amplitude slowly propagating electric field and accelerates the electrons at the location not too far from the conversion layer but far away from the cyclotron layer. In the third case, we chose $\theta = 60°$. Significant absorption is observed when the extraordinary wave tries to pass through the cyclotron layer.

*This work was supported by U.S.D.O.E. and NSF.

Would like to request an oral presentation.

A THEORY OF THE RELAXATION OF FINITE BETA TOROIDAL PLASMAS*

J. E. Brandenburg
Sandia National Laboratories, Albuquerque, New Mexico 87185

A modification of the Kruskal-Kulsrud[1] variational problem termed the "Sonic Bath"[2] is presented. An adiabatic, near perfectly conducting, toroidal plasma is assumed to relax from an intermediate equilibrium in a rigid, perfectly conducting chamber. This relaxation is assumed to take place in the presence of a bath of unconfined plasma on open-field lines. The plasma is assumed to relax through saturated shear Alfvén turbulence. A simple calculation, assuming the turbulence saturation scaling of Drake[3] et al. and linear coupling to magnetosonic waves in the bath gives an approximately fractional energy loss: $W_f = \varepsilon W_I$ where W_f and W_I are the final and initial magnetic energies respectively and ε is independent of energy. Using the assumption of Taylor[4] that global MHD invariants will determine the final equilibrium and the assumption that only small energy changes occur in the relaxation, it can be shown that the invariants are required to be quadratic by the fractional energy loss scaling. This is done by considering the relaxation as a linear transformation between states. Two quadratic invariants: Ψ^2 and $A \cdot B$, are shown to exist for the model and to give finite β, toroidal equilibria characterized by $P \alpha \Psi^2$ and $rB_\theta \alpha \Psi$. Equilibrium profiles will be presented and compared with experiment. In addition, the theory is extended to high aspect ratio toroidal devices such as the Reversed Field Pinch (RFP). A modified Bessel function model results with $8\pi P = \nu B_z^2$ and $A_z = \lambda B_z = J_o(\lambda \sqrt{1 + \nu}\, r)$, in agreement with a recent 2-D result of Montgomery and Turner.[5] Suydam stability analysis shows that these equilibria have an unstable core. A compound model is therefore proposed for the RFP with a force-free core and modified Bessel function model outer region. Comparison with experiments will be discussed.

*Work supported by the U. S. Department of Energy under Contract W-7405-ENG-48 while author was employed by LLNL.

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1D22

CHARACTER OF ION ORBITS IN AN ELLIPTICAL Z-PINCH

Jin-Soo Kim* and John R. Cary
Institute for Fusion Studies
University of Texas
Austin, Texas 78712

Regimes of deterministic and stochastic behavior of ion orbits are studied in an elliptical z-pinch for which the Hamiltonian is

$$H = \tfrac{1}{2}\{P_x{}^2 + P_y{}^2 + (P_z - \psi)^2\} ,$$

with $\psi = (\varepsilon x)^2 + y^2$ in convenient units, where x, y and z are cartesian coordinates with z in the axial direction.

Numerical study of surface of section plots shows that there are three regimes for this model system. The betatron type motions near the Hill's vortex and the small gyro-orbits far from the null are integrable. Stochastic behavior occurs in the transition region between betatron orbits and gyro-orbits. It is found that most of the ions of the FRC experiment[1] at LANL are in either the stochastic or betatron regimes.

1. W. T. Armstrong, R. K. Linford, J. Lipson, D. A. Platts, and E. G. Sherwood, Phys. Fluids 24, 2068(1981).

*Permanent Address: Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

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Poster Session

THEORY OF ELECTRON BEAM INJECTED MIRROR PLASMA

Avinash and R.K. Varma
Physical Research Laboratory
Navrangpura, Ahmedabad 380 009
INDIA

Abstract

In 2XIIB and Constance II mirror machines (1978, 80, 81) electron beams are injected parallel to the field lines to control the DCLC turbulence. To explain various observations of 2XIIB and Constance II we give a model based on resonant damping of DCLC by electron beam induced Langmuir plasmons. We have shown that linear growth rates of DCLC waves are modified. This modification depends on the beam power. Thus for beam power greater than a certain value the growth rates are enhanced and for values less than this value the growth rates are reduced. This has been observed in Constance II. To deal with the saturation in these modified DCLC modes we have obtained a closed set of equations to study the time evolution of ion distribution function. From this set of equations final ion and electron temperatures, ion life time inside the trap, saturated fluctuation level can be calculated. We have shown that the scattering of Langmuir plasmons by DCLC waves is much smaller than that due to ions; hence these modified DCLC waves will saturate when the growth due to ions is balanced by damping due to plasmons (not by loss cone filling as is the case usually). The plasmon damping reduces the fluctuation level which leads to an improvement of the ion life time inside the trap. From this set of equations we have further calculated the time for which the effect of beam will remain after the beam is turned off. For 2XIIB it turns out to be about ~ 400 μs which agrees well with the experimental observations. For Constance II we have calculated the saturated fluctuation level $W/nT \sim 6\times10^{-8}$ where W is energy density of DCLC waves and nT is particle energy density). This is quite reasonable (in 2XIIB the observed level was 8×10^{-8}).

NON-LINEAR THEORY OF FINITE BETA DRIFT WAVE TURBULENCE*

C. Beasley, J. Freidberg**, K. Molvig**, W. van Rij
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

ABSTRACT

Previous theory of universal drift mode turbulence indicates that small but finite beta ($\beta_e > m_e/m_i$) strongly affects saturation, leading to an anomalous thermal conductivity, χ_e, scaling inversely with density and in good agreement, in magnitude, with experimental observations on tokamaks.[1] The main features of the thermal conductivity formula were confined in a preliminary set of numerical results.[1] However, more recent detailed numerical studies[2] have found that the key analytic assumption of the previous theory, namely that the inductive potential, $\psi \equiv (\omega/k_{\parallel}c)A_{\parallel}$, becomes equal to the electrostatic potential, ϕ, at the rational surface, does not hold. In fact, $|\psi/\phi|$ is uniformly small, of order 0.1. This raises the questions of how the strong β_e dependence observed in χ_e could be produced, and what is the corresponding analytic justification. The present paper reformulates the finite beta theory, giving a new prescription for the non-linear theory, or renormalization procedure. We argue that the theory can, and should, be renormalized such that the resulting potential equations are self-adjoint (in contrast to the procedure in Ref. [1]). The eigenmode equations can then be solved by variational methods, eliminating the need for the heuristic approximation of Ref. [1]. We find that the strong β_e dependence of the shear damping persists in spite of small ψ, due to a strong coupling with the electromagnetic branch. In a limit where the diffusion coefficient can be found analytically, it can be written as,

$$D_{em} \approx \frac{D_{es}}{(1+2\beta_e(L_s/L_n)^2)^{3/2}} \qquad (1)$$

where D_{es} is the coefficient of the zero beta theory,[3] which is independent of density. Although Eq. (1) does not give a simple power law scaling with density, in the limited range of β_e where present experiments lie, $2 \times 10^{-3} < \beta_e < 5 \times 10^{-2}$, it is virtually indistinguishable from n^{-1} scaling. Similarly, in this range, Eq. (1) agrees in magnitude with the previous formula.[1] Dependences on other parameters, such as temperature, ion mass, and density and shear scale lengths are different and will be discussed.

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**Plasma Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.

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[2] C. Beasley, K. Molvig, W. I. van Rij, "Numerical Simulation of Finite β Nonlinear Drift Modes," paper given at 1981 Meeting of Division of Plasma Physics, APS (Bulletin of American Physical Society (26, 1010 (1981).
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Poster

1D25

Linear Oscillations in General Magnetically Confined Plasmas*

Liu Chen and Shih-Tung Tsai†
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

A systematic formalism for investigating linear electromagnetic perturbations in general magnetic field configurations is developed. The formalism employs the small adiabaticity parameter ρ/L_o and is valid for arbitrary frequencies. Here, ρ and L_o are, respectively, the Larmor radius and equilibrium scale length. Effects associated with plasma and magnetic field inhomogeneities as well as finite Larmor radii are contained. The specific case of axisymmetric tokamaks is then considered to illustrate the potential application.

†Address: Institute of Physics, Chinese Academy of Sciences, Beijing, The People's Republic of China

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Poster Session

DRIFT-IDEAL MAGNETOHYDRODYNAMICS*

A. B. Hassam and Y. C. Lee
Laboratory for Plasma and Fusion Energy Studies
University of Maryland
College Park, MD 20742

The ideal MHD equations are extended to include the frequency range $\omega \lesssim \omega_d$ and $\omega_{ci} \lesssim \omega$, where ω_{ci} is the ion cyclotron frequency and ω_d denotes any background particle drift frequencies. Such a frequency range is interesting for the EBT and Tandem-Mirror devices. Relative simplicity is achieved by restricting ourselves to collisional plasmas with cold ions. The resulting equations are linearized and a normal mode analysis performed to obtain the flute-like ($k_\parallel = 0$) modes of the plasma. Application is made to the uniform field case and to a z-pinch, $B_z = 0$, configuration. All five roots of the resulting dispersion relation are solved for and parametrically followed through the entire frequency domain. Pressure-driven and curvature-driven instabilities are identified and stability criteria are obtained.

* Work supported by the Department of Energy.

Poster

EFFECT OF MAGNETICALLY CONFINED ELECTRONS ON POTENTIAL FORMATION IN TANDEM-MIRROR THERMAL BARRIERS*

R. H. Cohen
Lawrence Livermore National Laboratory, University of California
Livermore, California 94550

In a tandem-mirror machine with thermal barriers, electron-cyclotron heating is applied in the barrier region to create a class of energetic, magnetically confined electrons which do not respond significantly to changes in the ambipolar potential. The intended result is an increase in the depth of the barrier potential. However, in machines where the plug and barrier are combined in a single cell, the presence of these electrons in the plug region affects the particle balance for the electrons electrostatically trapped there. The result is a reduction in the potential difference ϕ_{pb} between the plug and barrier regions (compared to a scenario with the same plug and barrier thermal-electron densities and temperatures but no energetic electrons) and thus a partial loss of the advantage gained by deepening the barrier. This effect is evaluated here using model hot-electron distribution functions and the formalism of Ref. 1, which gives the loss rate for particles trapped in a well in the presence of an arbitrary distribution of passing particles. Numerical examples appropriate for MFTF-B and TMX-Upgrade are presented.

Electron-cyclotron heating is also applied in the plug region, as a heat source. This application leads to an enhancement of ϕ_{pb} over that which would be obtained by heating from energetic ions alone, due to the relatively high level of diffusion at greater-than-thermal energies. Models for this beneficial effect are discussed.

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*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

1D28

Magnetic Field Lines and Particle Orbits in Toroidal Plasma Equilibria

Michael A. Marcal

New York University

A method is described to represent the magnetic field $\underline{B}$, obtained as a numerical solution of the equilibrium equations of ideal magnetohydrodynamics. The equilibrium solutions are produced by the computer code of Bauer, Betancourt and Garabedian [1]. The subsequent representation of $\underline{B}$, in the form of a series of Clebsch potentials, can then be used to follow magnetic field lines both in the plasma and vacuum regions. It is also possible to follow particle orbits. The ordinary differential equations are simple, and their integration remarkably quick.

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POSTER REQUESTED

Nonlinear Interaction of Drift Tearing Modes of Different Helicities*

H. R. Hicks†, B. Carreras, J. A. Holmes†, B. F. Masden†
Oak Ridge National Laboratory
Oak Ridge, TN 37830

We have proposed the interaction of tearing modes of different helicity[1] as a model for some tokamak disruptions. However, previous numerical results presented to support this hypothesis did not include kinetic effects. In particular, poloidal rotation due to diamagnetic effects was not included. This left open the question of whether the destabilization of the (m=3; n=2) tearing mode by the (m=2; n=1) mode would be materially modified by the rotation of both modes.

These nonlinear 3D calculations have now been redone with diamagnetic and gyroviscous effects added. The approach is a generalization of that used by Biskamp[2] and Monticello and White[3] for the single helicity (2D) case. We are able to recover their linear and nonlinear results when we go to the single helicity limit. For $m \geq 2$ modes there is poloidal rotation which ceases on island saturation, yielding a saturated state similar to the pure tearing mode.

In the multiple helicity case, we investigate the nonlinear interaction of the (m=2; n=1) and (m=3; n=2) drift tearing modes. We find that the destabilization of other modes by the (m=2; n=1) proceeds essentially as for the pure tearing mode.

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*Research sponsored by the Office of Fusion Energy, U. S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.
†Computer Sciences at Oak Ridge National Laboratory.
[1] B. V. Waddell, B. Carreras, H. R. Hicks, J. A. Holmes, D. K. Lee, Phys. Rev. Lett. 41, 1386 (1978).
[2] D. Biskamp, Nucl. Fusion 19, 777 (1979); D. Biskamp, Phys. Rev. Lett. 46, 1522 (1981).
[3] D. A. Monticello, R. B. White, Phys. Fluids 23, 366 (1980).

1D30

Relativistic Broadening Near Cyclotron Resonance

Kaya Imre* and Harold Weitzner
Courant Institute of Mathematical Sciences
New York University

ABSTRACT

Relativistic broadening of wave absorption (or emission) near electron cyclotron resonance in a warm plasma is investigated using the linearized relativistic Vlasov-Maxwell system. The unperturbed state is assumed to be isotropic, but not necessarily Maxwellian. The expansion parameter is $\eta = v_e/c$, where v_e is the electron thermal speed. It is assumed that the perpendicular refractive index, $n_\perp$, is of order one, and the wave frequency, plasma frequency and gyrofrequency are all large and comparable. The parameter $\alpha = v_e/n_\parallel c$ is assumed to be of an arbitrary order, thus results are uniformly valid for all values of $n_\parallel$, although the relativistic effects become negligible when $\alpha<1$. The conductivity tensor is reordered, and the dispersion relation appropriate for this problem is derived to the lowest significant order in η. The results are expressed in terms of the readily calculable (generalized) plasma dispersion function Z. In the special case of Maxwellian distribution, the results are algebraic in Z, and they do not involve integrations and/or infinite series of this function, thus leading to simple, efficient evaluations. The case of the perpendicular propagation, i.e., $n_\parallel = 0$, is obtained as a limiting case as $\alpha \to \infty$, and the previously published results for the Maxwellian case are rederived. Some inconsistencies in the literature dealing with the extraordinary mode are cleared.

*Permanent Address: The City University of New York, College of Staten Island, St. George Campus, New York 10301.

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Poster Session

NONADIABATIC PARTICLE MOTION IN EBT*

G. L. Chen, D. B. Batchelor, and C. L. Hedrick, Jr.
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

and

L. W. Owen
UCCND Computer Sciences
Oak Ridge, Tennessee 37830

Numerical calculations[1] and the results of various mirror and bumpy torus experiments indicate that the adiabatic invariant μ begins to break down when the ratio of the gyroradius to the magnetic scale length $\rho/L \geqslant 0.05$. In this work, we derive analytic expressions for $\Delta\mu/\mu$ in realistic vacuum magnetic fields by the method of stationary phase.[2] The analytic results are compared to those obtained by numerically integrating the defining equation for $d\mu/dt$. The dependence of $\Delta\mu/\mu$ upon magnetic field strength, mirror ratio, particle energy, and pitch angle will be illustrated. The effects on μ fluctuations of the hot electron ring diamagnetic currents in EBT are discussed and approximate analytic expressions are derived. Goals of this work include ascertaining possible effects of μ fluctuations on electron-cyclotron heating in EBT through resonant coupling with the microwave electric field, and on particle and energy loss through enhanced pitch angle scattering. Progress toward these goals will be discussed.

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*Research sponsored by the Office of Fusion Energy (OER), U.S. Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

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[2]R. H. Cohen, G. Rowlands, and J. H. Foote, Phys. Fluids 21, 627 (1978).

1D32

THEORY OF CURRENT PENETRATION IN THE PRETEXT TOKAMAK

J.C. Wiley, A.Y. Aydemir, A. Bhattacharjee, R.D. Hazeltine and S.M. Mahajan*
Institute for Fusion Studies
University of Texas
Austin, Texas 78712

The early, skin-current phase of the toroidal discharge in PRETEXT is characterized by an initial q-profile with a minimum of a few centimeters inside the limiter. As in other tokamak experiments, enhanced current penetration removes the minimum in a time much shorter than the classical skin time. Previous studies[†] of this process have relied on the overlap of islands associated with double tearing modes, centered at rational values of q on either side of its minimum. However, the observation of a wide spectrum of electrostatic potential fluctuations near the q-minimum, together with new results concerning the linear problem, suggest a different explanation: flux diffusion due to the interaction of many tearing-like disturbances whose islands remain negligibly small. Crucial features of such nonlinear interactions are studied by means of numerical simulation. The results are combined with a simple quasilinear treatment to provide input to a transport code.

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[†]See, for example, R.S. Granetz, I.H. Hutchinson and D.C. Overskei, Nucl. Fus. 19, 1587 (1979), and references therein.

Poster Session

EQUILIBRIA IN AXISYMMETRIC TANDEM MIRROR CONFIGURATION**

N. S. Kim and R. W. Conn
School of Engineering and Applied Science
University of California, Los Angeles, CA 90024

and

L. L. Lao
General Atomic Company
San Diego, CA 92138

High beta equilibria are required in configurational studies of tandem mirrors. We have been developing several full axisymmetric tandem mirrors, including the axisymmetric, electrostatically stuffed cusp configuration referred to as SKIPOLE,(1) and have been interested to compare it with the modified cusp tandem design developed by Logan.(2) For these purposes, a new high-β equilibrium code for axisymmetric tandem mirror systems has been developed based upon the approach used by Jaeger et al.(3) at Oak Ridge to analyze high-β EBT equilibria and incorporated into their FMHD2D code.

The governing equation for the axisymmetric equilibrium is

$$\Delta^* \Psi + \frac{1}{\sigma} \Delta\sigma \cdot \Delta\psi = - \frac{\mu_o r^2}{\sigma} \frac{\partial P_{11}(\psi,B)}{\partial\psi}$$

where $$\Delta^* = \frac{\partial^2}{\partial r^2} - \frac{1}{r}\frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2}$$

and $$\sigma = 1 + \frac{\mu_o(P_\perp - P_{11})}{B^2} \quad .$$

The quantity $2\pi\psi$ is the magnetic flux. The equation is solved by iterating the Δ^* operator until satisfactory convergence is achieved. High β equilibria are obtained for a number of axisymmetric tandem mirror configurations, including the LLNL modified cusp and the UCLA SKIPOLE cusp configuration. Stability of these equilibria with respect to interchange modes has been assessed and results for both the equilibria and stability at high β will be presented.

**Work supported by DOE.

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(3) E. F. Jaeger et al., "EBT Transport in 2-D Mirror Geometry with Finite Electron Annulus Pressure," ORNL/TM-7558 (December, 1980).

Analytical Representation of Ion Confinement in Tandem Mirror Plugs*

D. L. Galbraith and T. Kammash
University of Michigan
Ann Arbor, Mich. 48109

Because of its importance in modeling the plasma in current Tandem Mirror experiments, as well as for use in reactor studies, an analytical expression for the classical ion confinement in the plugs of these devices is indeed very desirable to have. A confinement formula based on a heuristic model which yields results that agree with a Fokker-Planck code over certain regions of parameter space has been produced[1]. In this investigation we derive a confinement formula which produces results in agreement with the code for TMX parameters as well as for those of a reactor. We find that the primary loss mechanism is the ion-ion scattering rather than a competition between this process and drag cooling of the ions on the electrons. This implies that the electron-ion collisions cause a cooling of the ion distribution but not affect individual ions independently of that distribution.

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*Work supported by DOE

1. B. G. Logan, A. A. Mirin and M. E. Rensink, Nuclear Fusion 20, 1613 (1980)

CORRELATION DECAY OF PERIODIC, AREA-PRESERVING MAPS

John D. Crawford, Allan N. Kaufman and Henry D.I. Abarbanel
Department of Physics
University of California
Berkeley, California 94720

and

Celso Grebogi
Laboratory for Plasma and Fusion Energy Studies
University of Maryland
College Park, Maryland 20742

and

James D. Meiss and John R. Cary
Institute for Fusion Studies
University of Texas
Austin, Texas 78712

A simple, analytical decay law for correlation functions of periodic, area-preserving maps is obtained by extracting the largest terms from the exact formula given by the characteristic-function method.[1,2] This law is compared with numerical experiments on the standard map. The agreement between experiment and theory is good when islands are absent, but poor when islands are present. In the latter case the correlation functions have long, slowly decaying tails. These are reflected in the diffusion coefficient by peaks which can exceed the quasilinear value by a factor of ten.

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Poster Session

1D36

RADIAL TRANSPORT IN NON-SYMMETRIC GEOMETRIES: EXPLICIT UPPER BOUND EXPRESSIONS AND APPLICATION TO TANDEM MIRROR

K. Hizandis and K. Molvig
Massachusetts Institute of Technology

R. Cohen
Lawrence Livermore Laboratory

I.B. Bernstein
Yale University

A general formulation of transport theory, specifically treating like- particle collisions, is developed for non-symmetric geometries, using the Lagrangian[1] picture. This theory provides a particularly simple method for calculating transport coefficients which is useful for devices such as Stellarators and Tandem Mirrors. We prove that the *explicit* piece of the transport coefficient processes such as test particle diffusion $\langle \frac{\Delta\psi\Delta\psi}{\Delta t} \rangle$, (which can be computed from single particle statistical properties using Maxwellian field and test particle distributions) provides a rigorous *upper bound* to the full transport coefficient. The more complex compound, *implicit* processes (involving perturbed distribution functions and not accessible from a simple Monte Carlo procedure), are always inward (for normal gradients) and can only reduce the full flux from its test particle value. The implicit fluxes have an associated variational principal, maximizing this inward flux. Since this flux contributes negatively to entropy production, there is, in effect a minimum principal for entropy production, familiar from the conventional theory. As an application of the formalism we consider neoclassical transport of electrons in a Tandem Mirror Machine. This is done by approximating the longitudinal invariant as the sum of a large axisymmetric part and a small non-symmetric perturbation. To lowest order in $\Delta\psi/\psi$, where $\Delta\psi$ measures the departure of the drift orbit from the flux surface, ψ, the flux is completely explicit. Closed form expressions are given for the like-particle and electron-ion scattering contributions to the electron particle and energy flux.

1D37

DRIVEN MAGNETIC RECONNECTION PROCESSES*

Bruno Coppi

Massachusetts Institute of Technology, Cambridge, MA, 02139

Magnetic reconnection processes that can take place around a neutral surface where the magnetic field vanishes or in a sheared field configuration are called "spontaneous" when the driving factor is the current density gradient that is characteristic of these configurations, and "driven" when the driving factor is different. We have found a new type of mode producing magnetic reconnection in a neutral sheet where the ions can be treated as cold and the electron distribution has a slight distortion from a Maxwellian equivalent to a small temperature anisotropy with the $T_{e\perp} \gtrsim T_{e\parallel}$. The relevant growth rate is about

$$\alpha_a (2T_e/m_i)^{1/2} k_\parallel$$

where $k_\parallel$ is the longitudinal wave number and $\alpha_a \simeq (T_{e\perp}/T_{e\parallel})-1$. The perturbed magnetic configuration that is produced is characterized by four parallel strings of magnetic islands centered around the neutral surface, as the transverse perturbed magnetic field ($\tilde{B}_x$) is an odd function of x, the distance from this surface.

The dispersion equation for the mode amplitude is solved analytically[1] under the assumption that a transverse anomalous electrical resistivity $\eta_\perp$ can be introduced. The width of the layer over which the mode amplitude is localized is of the order of

$$\delta \simeq \lambda_m^{1/2} (\mathcal{D}_m/\omega_s)^{1/4} \alpha_a^{1/8}$$

where $\omega_s^2 = k_\parallel^2 T_e/m_i$, $\mathcal{D}_m = \eta_\perp c^2/4\pi$ and λ_m is the scale distance for the gradient of the equilibrium magnetic field.

When the electron distribution is isotropic, and the ion temperature is not negligible a mode with even parity of $\tilde{B}_x$ can be driven unstable by the anisotropy of the ion distribution. The relevant growth rate, found in the absence of an appreciable anomalous electrical resistivity, is of the order of $\gamma \simeq \omega_s (T_i m_e/m_i T_e)^{1/4} (T_{i\perp}/T_{i\parallel} - 1)$.

In both cases the rate of reconnection and the width of the layer over which this can take place are larger than those typical of "spontaneous" reconnecting (tearing) modes.

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*Sponsored in part by the A.F. Geophysical Laboratory (AFSC).

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A Variational Principle for Plasmas Confined by Nonsymmetric Magnetic Fields*

S. P. Hirshman
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

ABSTRACT

A variational principle is presented which minimizes the total energy (magnetic field and fluid plasma) $W = \int(B^2/2 + p)dV$ of a plasma confined in a general, nonsymmetric magnetic configuration. The minimum energy states correspond to MHD equilibria, when the magnetic field is written in the covariant form $\vec{B} = -\nabla\Phi + J(p)\nabla\theta - I(p)\nabla\phi - \nu\nabla p$. Here, $J'(p)$ and $I'(p)$ are the toroidal and poloidal current fluxes, respectively (prime denotes $\partial/\partial p$), $\phi(\theta)$ the toroidal (poloidal) angle, and ν the helical current potential due to internal plasma currents induced by external windings and toroidicity. Variations of W are performed with respect to the dependent variables $\Phi(\vec{x})$, $\nu(\vec{x})$ and $p(\vec{x})$, and the resulting Euler equations lead respectively to an elliptic equation for Φ $(\nabla \cdot \vec{B} = 0)$ and hyperbolic equations for p $(\vec{B} \cdot \nabla p = 0)$ and ν $(\vec{B} \cdot \nabla\nu + \vec{B} \cdot \nabla\theta J' - \vec{B} \cdot \nabla\phi I' + 1 = 0$, which is the $\nabla\theta \times \nabla\phi$ component of the pressure balance, $(\nabla \times \vec{B}) \times \vec{B} - \nabla p = 0)$. The present formulation can treat systems with multiple magnetic axes, since a flux surface (contravariant) representation[1] for $\vec{B}$ is not assumed. Also, the magnetic potential Φ is easily related to the external coil currents, thus facilitating implementation of real boundary conditions. Since the magnetic surfaces p = constant are only obtained approximately (but variationally), many of the problems associated with the exact solutions of magnetic differential equations on rational surfaces should be mitigated by this formulation. Finally, all the variational quantities are field-related scalars and are thus amenable to eigenfunction expansions (e.g., eigenfunctions of the Helmholz operator).

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*Research sponsored by the Office of Fusion Energy (OER), U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

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POSTER

KINETIC BALLOONING MODES IN QUADRUPOLE-STABILIZED TANDEM MIRRORS*

W. M. Nevins and L. D. Pearlstein
Lawrence Livermore National Laboratory, University of California
Livermore, California 94550

We present a quantitative analysis of the limit on β due to "large-n" ballooning modes in quadrupole-stabilized tandem mirrors, including both "1/n corrections" and kinetic terms. We will focus on three particular tandem mirror configurations; the TMX-Upgrade experiment, the original MFTF-B design, and a modification of this design which has internal axisymmetric barrier-cells like the Tara experiment at MIT.

Einstein-Brillouin-Keller (EBK) quantization methods (a multidimensional extension of WKB) are used to solve for the perpendicular structure of the ballooning mode eigenfunctions. In previous work we used WKB to solve an analytic model of the local dispersion relation. We compare these previously reported analytic predictions with results obtained by numerically integrating the ray trajectories. We find that the the analytic model works well near ideal MHD marginal stability, but it proves unreliable when β_c significantly exceeds the ideal MHD limit. In this regime, the EBK quantization conditions must be obtained numerically. Nevertheless, our main previous conclusion holds; the "1/n corrections" and kinetic terms have such a strong stabilizing effect that it is unlikely that large-n ballooning modes will limit the center cell beta in any current or future tandem mirror experiments.

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CONSIDERATION OF STABILITY LIMITS IN FUTURE EBT DEVICES*

N. A. Uckan and D. A. Spong

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Limitations imposed on core beta and pressure profiles, ring scale lengths, and power balance by stability constraints are critical in EBT in the determination of the operating windows of experiments and in the assessment of desirability of a reactor. Theoretical models[1,2] to date indicated existence of several modes which can roughly be divided into low ($\omega < \omega_{ci}$), intermediate ($\omega \gtrsim \omega_{ci}$), and high ($\omega \sim \omega_{ce}$) frequency modes. The low and intermediate frequency modes (core interchange, hot electron interchange, compressional Alfvén wave, etc.) are expected to determine the operating boundaries, whereas high frequency modes (Whistler, etc.) tend to impact the ring and core energy balances. Typically, these modes impose restrictions on upper and lower limits on n_{core}/n_{hot} and T_{core}/T_{hot}, upper limit on β_{core}, lower limit on β_{hot}, etc.; which are determined by ring scale length Δ, radius of curvature R_c (local and/or field line averaged), $q_o = \omega_{drift\text{-}hot}/\omega_{ci}$, anisotropy $T_{\parallel}/T_{\perp}$, etc. In future devices, the most restrictive of these modes appear to be hot electron interchange and core interchange, both of which affect the ring and core power balance. The boundaries of the operating window and ring power balance are calculated within the constraints of present stability theory for future EBTs. Because some of these constraints are derived in limits where the approximations break down for reactor like devices and also because most of the present models fail to agree with experiments over at least some parameter ranges (i.e., theory predicts instability while experiment is observed to be stable), a parametric study is performed to indicate the sensitivity of the results to various assumptions/uncertainties involved. Some of the geometric details of the magnetic field are incorporated in the analysis in order to treat profile effects adequately. Results will be discussed.

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*Research sponsored by the Office of Fusion Energy OER, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

[1]See papers in *EBT Stability Theory: Proceedings of the Workshop*, CONF-810512 (N. A. Uckan, editor).

[2]See papers in *Hot Electron Ring Physics: Proceedings of the Second Workshop*, CONF-811203 (N. A. Uckan, editor).

1D41

POSTER SESSION

ELECTRON THERMAL CONDUCTIVITY IN TOKAMAKS*

T. Yamagishi, C. S. Chang, D. K. Bhadra, and C. S. Liu
General Atomic Company
San Diego, California

ABSTRACT

Electron diffusion in tokamaks is studied by making use of the test particle model taking into account the toroidal effect and the nonlinearity of resonance broadening in the presence of magnetic damping. The electron diffusion coefficient is described in terms of the Lorentz force fluctuation and the resonance function.[1] The Lorentz force is expressed in terms of density fluctuation and the parallel component of dielectric tensor through the Ampere's law. The characteristics of the resonance function in a the sheared magnetic field are examined in detail, and an approximate formula is applied to evaluate the parallel electric conductivity and the electron diffusion coefficient. When the density fluctuation is given by the simple saturation condition and $k_\perp$ is chosen to maximize the diffusion coefficient,[2] the resonance broadening tends to a modified Ohkawa's formula.[3] The toroidal effect on the unperturbed particle orbit induces low frequency geometrical sideband resonances. The effect of these sideband resonances on the diffusion coefficient will be discussed.

[1]Yamagishi, T., Phys. Fluids 22, 2431, 1979.
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[3]Ohkawa, T., General Atomic Company Report GA-A14433, 1977.

*Work supported by Department of Energy Contract DE-AT03-76ET51011

SIMULATION STUDIES OF EFFECTS OF HOT ELECTRON RING ON FLUTE INSTABILITIES FOR AN EBT-LIKE GEOMETRY*

Y. Ohsawa** and J. M. Dawson
University of California, Los Angeles, CA 90024

Stability and beta limits of EBT is studied by using a 2-1/2 dimensional electromagnetic and relativistic particle code, which models flute instabilities driven by an inhomogeneous magnetic field in an EBT-like slab configuration. A hot electron ring is shown to be effective in suppressing low-frequency interchange modes. No evidence for excitation of magneto acoustic instabilities has been seen. Our present simulations show stabilization of core plasma β's up to the order of the hot ring beta. Higher core β's show a complicated behavior. Effects of position of the hot ring and $E \times B$ shear flows are investigated.

*This work is supported by U.S.D.O.E.

**On leave from Institute of Plasma Physics, Nagoya University, Nagoya 464, Japan

LINEAR THEORY OF ELECTROMAGNETIC STABILITY IN A PARABOLIC Q-PROFILE

R. D. Hazeltine
Fusion Research Center

and

S. M. Mahajan
Institute for Fusion Studies
The University of Texas at Austin
Austin, Texas 78712

In the early stages of a tokamak discharge, the current flows in a narrow region near the plasma edge, giving rise to a parabolic profile for the safety factor. The linear electromagnetic stability of the plasma for this q-profile is investigated within the framework of resistive magnetohydrodynamical equations.

The eigenvalue problem is formulated in terms of an integral equation for the perturbed current $\tilde{J}(x)$ and solved variationally. It is found that the tearing mode can either appear as the "double-tearing" mode or the "centered" mode. The "double-tearing" mode is characterized by two peaks near the two mode rational surfaces and is unstable even in the absence of external driving magnetic energy, i.e., there is an intrinsic, effective $\Delta' > 0$, which comes from a linear coupling between the two peaks. The "centered" mode is peaked at the minimum of q and has a growth rate somewhat larger than the "double-tearing" limit. The linear theory is applied towards explaining the observed anomalous current fluctuation.[1]

[1] See J. C. Wiley et al., "Theory of Current Penetration in the Pretext Tokamak", in this meeting.

Poster Session

POSTER SESSION

WEAK TURBULENCE THEORY OF BALLOONING MODES*

R. W. Moore, D. K. Bhadra, R. R. Dominguez, and C. S. Liu
General Atomic Company
San Diego, California

ABSTRACT

Recent high beta neutral beam heated tokamak experiments have demonstrated degradation of energy confinement with increasing beam power. In this paper, high toroidal mode number ballooning modes are examined for their dependence on neutral beam injection effects, specifically beam current, plasma rotation, and hot ion drift resonances. We start with the results of the linear kinetic theory of ballooning modes[1] including finite Larmor radius effects, background plasma rotation, anisotropic pressure, and hot ion drift resonance effects. Self consistent non-linear eigenmode equations are derived to demonstrate saturation of high-n ballooning modes and their effect on plasma transport.

[1]Dominguez, R. R, et al., "Neutral Beam Effect on Ballooning Mode Stability," paper presented at Sherwood Theory Meeting, Santa Fe, 1982.

*Work supported by Department of Energy Contract DE-AT03-76ET51011

1982 SHERWOOD THEORY MEETING
Santa Fe, New Mexico, April 26-28

SPECTRUM OF DRIFT WAVE TURBULENCE IN A SHEARED MAGNETIC FIELD

A.K. Sen*, S. Kim*, Columbia University
New York, N.Y. 10027

T. Tange, Hiroshima University
Hiroshima, Japan

The nonlinear saturation of drift wave type instability in a sheared magnetic field is studied. The nonlinear wave potential is expanded in linear sheared eigenfunctions involving the fundamental (n=0) and first order (n=1) Hermite functions to yield two mode coupling equations. The coupling to the stable first order radial modes provides the saturation mechanism. The system can be reduced to a single integral equation which has been solved analytically to yield a stationary spectrum in the long wavelength regime ($k_\perp \rho_i << 1$). This solution is matched to a spectrum controlled by the non-linear ion Landau damping at shorter wavelengths ($1 < k_\perp \rho_i < 1$). Alternatively, the solution is matched to the solution of Hasegawa-Mima equation at shorter wavelengths, where shear may be considered defeated by the dominance of the non-linear term over the linear term and the resulting isotropic turbulence. In both cases the spectrum exhibits a peak in the long wavelength region where the new mechanism is prevalent. The physical mechanism responsible for the creation of stationary spectrum is the real energy drain provided by the mode coupling of fundamental radial modes with the stable higher order radial modes. This resolves the paradox of unlimited energy accumulation at the longest wavelength due to the inverse cascade of the usual weak turbulence theories based on conservative resonant 3-wave mode coupling.

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Prefer: Oral Session.

Submitted by

A. K. Sen 3/15/82.

Amiya K. Sen

MAGNETIC RECONNECTION DRIVEN BY THE COALESCENCE INSTABILITY*

A. Bhattacharjee, F. Brunel and T. Tajima
Institute for Fusion Studies
University of Texas
Austin, Texas 78712

It is well known that a periodic chain of magnetic islands, produced, for example, by helical perturbations on an axisymmetric equilibrium, are subject to the coalescence instability[1,2]. Beginning with a modified form of an exact hydromagnetic equilibrium which exhibits such a periodic chain of islands in slab geometry, we study the nonlinear evolution of the coalescence instability by using a 2 1/2-D MHD Particle Simulation Code[3] which advances in time the *full* set of resistive MHD equations. We concentrate on the effects of the magnitude of the toroidal field and plasma compressibility on the rate of magnetic reconnection at the x-point. For a force-free, finite beta equilibrium with a large toroidal field, we recover approximately earlier results[2] obtained from a two-dimensional study for the case in which the plasma is regarded as incompressible. In the nonlinear phase, for $S \simeq 2 \times 10^3$ and zero viscosity, the destruction of flux at the x-point proceeds linearly with time. For smaller values of the toroidal field, the destruction of flux is somewhat faster. The effect of plasma compressibility on the rate of reconnection will be reported. Implications for the steady-state reconnection models of Sweet-Parker and Petschek will be discussed.

*Work supported by the U.S. Department of Energy Contract No. DE-FG05-80ET-53088.

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Poster Session

Determination of the Perturbed Density Distribution Function for a Semi-Infinite Plasma

By

M. R. Sands and B. D. Ganapol
Department of Nuclear and Energy Engineering
University of Arizona

Utilizing the linearized Vlasov equation and Ampère's law, the perturbed density distribution function for a semi-infinite plasma is analytically determined. Of the various methods available for the determination, one method, namely, the expansion in perturbed collisional components, lends itself most easily to a numerical evaluation. This solution methodology has proven to be extremely successful in solving time-dependent problems in rarefied gas dynamics[1] and neutron transport theory[2]. The solution technique takes advantage of the particular form of the perturbed collisional components to reduce the governing equations to an infinite set of singular partial differential equations which can be solved in the complex plane. From the reconstruction of the perturbed collisional component in terms of integrals over boundary values, a numerical quadrature scheme can be developed to generate accurate numerical results. In addition, the perturbed density distribution at the wall can be generated via the well-known principle of invariance[3]. Numerical results for a Maxwellian equilibrium distribution will be presented.

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EXCITATION OF GLOBAL EIGENMODES ASSOCIATED WITH THE ALFVEN DISCRETE SPECTRUM

K. Appert, R. Gruber, F. Troyon, and J. Vaclavik

Centre de Recherches en Physique des Plasmas
Association Euratom - Confédération Suisse
Ecole Polytechnique Fédérale de Lausanne
CH-1007 Lausanne / Switzerland

Recent experimental results obtained on the Lausanne TCA Tokamak show resonance peaks at frequencies just below the lower edge of the Alfvén continuum. These peaks can be interpreted by means of the ideal MHD theory. In particular, we shall show that the resonance peaks can be related to the excitation of eigenmodes which are associated with the Alfvén discrete spectrum.

We propose to use these resonance effects to heat the Tokamak plasma and to call this new type of heating: "Alfvén Eigenmode Resonance Heating" (AERH). Calculations performed for a driver system show that the efficiency of such a heating scheme increases with decreasing toroidal wavenumber n. An optimum is obtained for n = 0. Since the resonant frequency strongly depends on the equilibrium profiles, frequency tracking is necessary.

Poster session

Plasma production and heating

HEATING AND SUPERADIABATICITY FOR SINGLE AND MULTIPLE FREQUENCY ECRH*

T. D. Rognlien
Lawrence Livermore National Laboratory, University of California
Livermore, California 94550

ABSTRACT

A common assumption in calculations of the electron heating rate for electron cyclotron waves is that the process is stochastic so that a quasilinear model applies. However, recent experimental results in the SM-1 mirror device at TRW, Inc., show that using closely-spaced frequency components increases the heating efficiency; these results can not be explained by a quasilinear model. We thus do not make any assumption about stochasticity, and investigate the heating caused by monochromatic waves both analytically and numerically with a test particle code that includes collisions. If collisions are ignored, stochastic heating replaces superadiabatic motion when the wave amplitude is sufficient to produce intrinsic stochasticity by resonance overlap. The use of two or more waves with different frequencies increases the number of resonances and thus the chance of resonance overlap; a frequency separation of the axial bounce frequency is optimum for two waves. A spectrum of axial wavenumbers making up a standing wave does not increase the number of resonances and thus does not increase stochasticity. Pitch-angle collisions can also produce significant decorrelation between the wave and particle owing to the large geometrical enhancement of the gyrophase diffusion in an inhomogeneous magnetic field. For fundamental heating at SM-1 parameters, we find that using two frequencies instead of one increases the amount of heating at an energy of ~10 keV. Collisions are also significant in producing stochasticity at this energy. Calculations for ECRH on the tandem mirror TMX-Upgrade at LLNL for an energy of 50 keV show that, for one wave at full ECRH power, stochasticity is assured for both fundamental ($\omega = \omega_c$) and second harmonic ($\omega = 2\omega_c$) heating by resonance overlap. At lower power levels, stochasticity is assured by collisional gyrophase diffusion.

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ORAL SESSION

OXYGEN CONTAMINATION DIAGNOSED WITH THREE VUV SPECTRAL LINES*

C. Lilliequist, A. G. Sgro, E. Caramana, N. H. Magee,
J. Abdallah, and A. L. Merts
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

C. Crume
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

A vuv oxygen radiation program for ground level transitions has been combined with a recently updated coronal equilibrium ionic distribution model to search for spectral lines with radiation rates that were relatively constant over the temperature range of 5 to 30 eV. Of the 77 lines considered by the oxygen radiation program, the 1658 Å line of O III, the 1401 Å line of O IV, the 1218 Å line of O V, and the 1032 Å line of O VI met the criteria that the radiation rate should vary by less than two over the temperature range (four in the case of O VI) and their minimum be at least 5×10^3/s sr. Multiplying these radiation rates by their respective coronal equilibrium ionic distributions shows that the O III line is not appropriate to our purpose because it is not useful above 8 eV. The other three lines could be used over the range: O IV - 7 to 14 eV, O V - 12 to 22 eV and O VI - 17 to 31 eV. Thus under coronal equilibrium conditions, simultaneous measurements of radiation in line-pairs with overlapping useful temperature regimes could be used as a consistency check or to question the existance coronal equilibrium.

For a transient plasma atomic line emission can only be used reliably as a disgnostic tool in conjunction with a fully time dependent plasma modeling code. If the plasma starts as neutral oxygen with $n_e = 1 \times 10^{14}$/cc, the time dependent ionization rate equations indicate that these three lines will first be seen in significant quantities only after the first 70 μs, well before reaching coronal equilibrium. Thus, in the time interval between first possible observation and the completion of thermal relaxation (about 1 ms) one expects to need such a fully time dependent code.

In general, the emission rate is give by $R = \int n_{0i}\,(t,T,n_0)n_e(t)\,C(T)$. For the time dependent case even though the "near constancy" of the emissivity, C(T), over this considerable temperature range allows it to be removed from under the integral, one still must evaluate the time dependence of $n_{0i}(t)$ under the integral. The effects of starting with different densities and initial conditions are under investigation.

*Work performed under the auspices of the USDOE.

TOROIDAL RFP EQUILIBRIUM AND STABILITY AGAINST IDEAL AND RESISTIVE LOCALIZED MODES*

R. Y. Dagazian
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

M. S. Chance
Princeton Plasma Physics Laboratory
Princeton, New Jersey 08544

Toroidal RFP equilibria with rather high values of beta are numerically[1] determined. The stability of such equilibria is examined against Mercier and ideal ballooning modes. When ideally stable the equilibria are further tested for stability against resistive ballooning.[2] Our investigations are motivated by recent experimental observations of density fluctuations in the ZT-40 device, which strongly exhibits a ballooning character.[3]

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*Work performed under the auspices of the USDOE.

An Analytical Solution to a Model Fokker-Planck Equation

by

E. B. Parlette
B. D. Ganapol

Department of Nuclear and Energy Engineering
University of Arizona

The Fokker-Planck equation for fast ions undergoing small-angle scattering without energy loss is solved analytically for an isotropic burst of ions appearing at the central plane of an infinite homogeneous medium. The goal is to derive a density distribution function which can be numerically evaluated in order to benchmark numerical solution algorithms. The Fokker-Planck equation is expanded into multiple collision components, and due to a similarity transformation, an infinite set of singular reduced equations not heretofore found can be derived. These equations are readily solved in the complex plane through the use of a Cauchy representation yielding an expression which can be evaluated numerically with the resulting values used to benchmark numerical solutions obtained via standard numerical methods. The resulting solutions are expressed as summation of the delta function and its derivatives which when integrated over angle gives rise to a spatially constant scalar density behind the wave front. A similar procedure can be used to solve model problems that include energy loss.

RENORMALIZED PARTICLE CODES AND THEIR APPLICATIONS

J. N. Leboeuf and T. Tajima
Institute for Fusion Studies
The University of Texas at Austin
Austin, Texas 78712

A class of long time-step partially implicit (but primarily explicit) codes has been developed in 1 to 2½ dimensions. Poisson's equation is renormalized by using the constant acceleration approximations for the future values along the static magnetic field direction; no renormalization is invoked in the perpendicular directions because of guiding-center electron and ion dynamics.[1] As we discussed in [1], the time-step Δt can be arbitrarily large for a uniform plasma as long as a large enough particle size is taken, because the Courant condition $\Delta t \lesssim \Delta/v_{th}$ can be arbitrarily relaxed by having $v_{th} \to 0$ (v_{th}: thermal speed). When a large enough particle size is chosen, the collisionality of the code is much lower than that of the explicit version even for small v_{th}: when a smaller particle size is taken, the orbit deviates from a straight line and the code does not behave. The polarization drift effects[2] have been considered in the perpendicular directions, giving rise to another renormalization of Poisson's equation. An application of the 1-D code to ion clump simulation will be discussed.

Work supported by DOE grant DE-FG05-80ET-53088.

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Poster Session

STABILIZATION OF THE INTERNAL KINK MODE IN FINITE BETA TOROIDAL PLASMAS*

J.J. Ramos and G.B. Crew
Massachusetts Institute of Technology, Cambridge, MA, 02139

The stability of the internal kink mode in a finite beta model confinement configuration is investigated using the ideal magnetohydrodynamic (MHD) energy principle. Taking this mode to have a poloidal dependence dominated by m=1 and m=2 harmonics, it is possible to reduce the potential energy functional to a quadratic form in a single radially dependent variable. We then demonstrate analytically that the mode becomes stable at sufficiently high beta, independent of its toroidal mode number.[1] Numerical estimates of the "second" marginal stability point show that this stabilization can occur for values of beta consistent with the assumptions of the model equilibrium. We calculate the linear growth rate of the internal kink in our model, which asymptotically matches the result of the standard low beta theory.[2] Thus we obtain the variation of the mode growth rate for arbitrary beta.

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*Work supported by the United States Department of Energy.

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SAYTR2: A d-d Fuelled Tandem Mirror Reactor

D. Dobrott and D. C. Baxter
Science Applications, Inc.
La Jolla, CA 92037

G. W. Shuy
University of California at Los Angeles
Los Angeles, CA 90024

A d-d fuelled barrier tandem mirror reactor (BTMR) design, SAYTR2[1], has been recently suggested. This design is a modification of an earlier one developed at UCLA, SAYTR[2]. The modification is concentrated on four high leverage issues: (1) high central cell beta, (2) high barrier mirror ratio, (3) use of a negative barrier potential, and (4) use of a barrier drift pump. The new design incorporates an axi-cell barrier, and a ying-yang anchor. Results from finite beta equilibrium and flute stability computations and preliminary power balance results are presented.

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1E12

SPECTR3: A 3-D MHD CODE FOR THE RFP*

D. D. Schnack and E. J. Caramana
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Recently significant progress has been made in the understanding of two-dimensional helical nonlinear resistive MHD activity in the Reversed-Field Pinch (RFP).[1] However, the central issues of RFP physics such as the nonlinear interaction of unstable modes with different helicity and the attainment and maintenance of field reversal due to turbulent dynamo action require three-dimensional calculations. In this paper we present a new time-dependent resistive MHD code that will be used to address these problems. Cylindrical geometry and realistic boundary conditions are used. Finite-difference representation in the radial direction and pseudo-spectral representation in the azimuthal and axial directions are employed. The temporal differencing is leap-frog. Additional numerical and computational details, and preliminary results, will be presented.

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*This work performed under the auspices of the USDOE.

COMPUTER SIMULATIONS OF ION CYCLOTRON RESONANCE HEATING IN TOKAMAKS

M. Makino
Institute of Plasma Physics
Nagoya, Japan

N. N. Leboeuf and T. Tajima
Institute for Fusion Studies
The University of Texas at Austin
Austin, Texas 78712

and

K. Whang
Department of Physics
The University of California at Los Angeles
Los Angeles, California 90024

Computer simulations of ion cyclotron resonance heating have been performed in slab approximation to tokamak geometry on 1-2/2-D and 2-1/2-D electromagnetic codes with absorbing boundaries.[1] A single q surface is modeled and the toroidal field varies as 1/R. Typically a majority deuterium (90 per cent D) and minority hydrogen (10 per cent H) plasma is considered. The fast Alfvén wave is generated by either toroidal or poloidal antennae on the low field side. Our two-dimensional results show minority heating and strong electron heating due to Landau damping. Our one-dimensional results show strong perpendicular minority heating only. The maximum minority temperature achieved scales as stronger than a first power of the pump-wave amplitude.

Work supported by US-DOE and Japan MOE.

[1] T. Tajima and Y.C. Lee, J. Comp. Phys. 42, 406 (1981).

Poster Session

1E14

PARTICLE-LIKE NATURE OF ZERO-FREQUENCY WAVES*

Cheng Chu
General Atomic Company
San Diego, California 92138

ABSTRACT

By using transverse electromagnetic waves in plasma as an example, the particle-like nature of zero-frequency waves is demonstrated. It is shown that zero-frequency waves correspond to the free-particle state of normal coordinates whereas finite frequency waves correspond to that of harmonically oscillating normal coordinates. It is emphasized that for zero-frequency waves with $\omega = 0$, the energy is finite and does not go like $\hbar\omega$. Magnetostatic modes[1,2] and force-free fields $\nabla \times \vec{B} = k\vec{B}$ with k a constant are examples of zero-frequency waves.

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*Work supported by Phillips Petroleum Company and General Atomic Company under Joint Research and Development Agreement (GA Reference No. 01341).

FINITE LARMOR RADIUS EFFECTS ON CURVATURE-DRIVEN INSTABILITIES IN HOT ELECTRON PLASMAS*

J.W. Van Dam, H.L. Berk, C.Z. Cheng†, and M.N. Rosenbluth
Institute for Fusion Studies
University of Texas
Austin, Texas 78712

A recent radial eigenmode analysis[1] of curvature-driven instabilities in a hot electron EBT plasma indicated that stability disappears within a band of moderate mode number values, due to resonance of the high-frequency ($\omega \gtrsim \omega_{ci}$) hot electron interchange and modified compressional modes whose radial wavelengths are short compared to the half-width Δ of the hot electron annulus ($k_r\Delta > 1$). Layer modes, which are nearly constant across the annulus region ($k_r\Delta \to 0$), were found to be unstable for all low m values, unless the ion density is sufficiently high. Numerical solution[2] of the radial mode differential equation further showed that the modes naturally tend to be short wavelength at high m values, becoming layer-like at low m. However, this theoretical prediction of instability neglected gyroradius effects.

Using an arbitrary frequency gyrokinetic equation,[3,4] we have generalized the full eigenmode equations to include the effects of both finite ion and energetic electron Larmor radii in an axisymmetric system. For flute modes in the purely radial z-pinch model, a variational treatment shows that FLR effects can simultaneously stailize both the short wavelength background plasma interchange and compressional modes. However, the layer modes are only weakly affected, for arbitrarily large gyroradii. An approximate analysis of the coupling to the shear Alfvén mode in a bumpy cylindrical system with axial variation shows that ballooning effects stabilize only very low m-number modes.

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†Permanent address: Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540.

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1E16

MHD Ballooning Modes in EBT

Young-ping Pao
Courant Institute of Mathematical Sciences
New York University

ABSTRACT

We consider a straight axisymmetric bumpy cyclinder with periodic end conditions as a model for EBT device and study MHD modes for large mode number. Lowest order equations lead to a one-dimensional eigenvalue problem along the field line. Higher analysis is also carried out. Comparison with the tokamak results is made. Since the system has no shear, no ballooning transformation is needed. The possibility of steady-state oscillations with high mode numbers is also discussed.

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GUIDING CENTER PLASMA SIMULATION

A. Y. Aydemir, D. C. Barnes, and T. Kamimura*
The Institute for Fusion Studies
University of Texas
Austin,Texas 78712

A method for low frequency simulation of strongly magnetized plasmas is described. The usual cloud-in-cell particle simulation method is modified to retain only the gyroaveraged particle motion and conjugate gyroaveraged sources to second order in the Larmor radius. The resulting model is appropriate for studying low frequency behavior of strongly magnetized plasmas with time step dt satisfying $wdt \leq 1 \leq w_c dt$, where w is the mode frequency and w_c the cyclotron frequency.

Numerical results for single particle motion in varying electromagnetic fields are obtained and compared with theory. The plasma response represented by a summation over individual particles is compared with the plasma conductivity from theory. Finally, the results of a self consistent, two dimensional, electrostatic simulation of a gravitationally driven instability are described.

* Permanent Address: Japan Institute of Plasma Physics/Joint Institute for Fusion Theory, Nagoya, Japan.

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POSTER SESSION

3D MHD EQUILIBRIUM CALCULATION OF THE CLEFTRON

T. S. Wang and T. Ohkawa
General Atomic Company
San Diego, California

ABSTRACT

The Cleftron is an extremely simple single coil stellarator. The coil is composed of several parts: a center post which produces the main toroidal field, a helical winding which produces the transform on the outside region and the upper/lower joints which connect the center post and the helical windings.

Vacuum field calculations using a field-line tracing code show the existence of flux surfaces. The plasma-cross section is roughly dee-shaped with a small aspect ratio ~ 2. The magnetic axis is helical due to the strong $\ell=1$ helical component. There is a separatrix on the larger major radius side of the plasma, beyond which field-lines are not closed. The plasma elongation is between 1.3 and 2. The equilibrium β limit will be accessed by using a 3D MHD equilibrium code.[1] Results of the optimization of the Cleftron configuration will also be presented.

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Abstract for 1982 Sherwood Theory Meeting

SOLITONS GENERATED BY BOUNDARY MOTION

C. K. Chu, L. W. Xiang

Columbia University

The Korteweg-deVries equation

$$u_t + uu_x + \varepsilon u_{xxx} = 0$$

is solved for a mixed initial-boundary value problem in the x-t quarter plane; i.e., the solution $u(x,t)$ is sought for $x > 0$, $t > 0$ with initial condition of rest $u(x,0) = 0$ for $x > 0$, and with boundary condition $u(0,t)$ prescribed at $x = 0$. Physical problems represented by this model problem include, among others, the generation of ion-acoustic solitons by a prescribed potential at a fixed grid, the generation of solitary waves in a water tunnel by the programmed motion of a piston or of a gate controlling the water height at one end, etc.

As is to be expected from studies of pure initial-value problems for the KdV equation, solitons appear in this case. We present a numerical and analytical study of the relationship between the boundary conditions prescribed and the solitons produced. In particular, finite-duration boundary motions result in a finite number of solitons, while impulsively-started boundary motions (Heavyside functions) result in repeated solitons or conoidal waves. An unexpected simple relationship is found between the boundary values prescribed and the soliton heights and speeds that result. Relations between these waves and collisionless shocks are also illuminated in this context.

Work supported in part by USDOE.

STABILITY OF RELAXED SPHEROMAK EQUILIBRIA*

G. Marklin and A. Bondeson
Laboratory for Plasma and Fusion Energy Studies
University of Maryland
College Park, Maryland 20742

According to the Taylor relaxation theory[1] any fast ($\tau_{formation} \sim \tau_{Alfvén}$) turbulent spheromak formation scheme is likely to produce a relaxed equilibrium where $\vec{J} = \lambda\vec{B}$ with λ = constant inside the plasma and $\lambda = 0$ outside. Rosenbluth and Bussac[2] have studied the stability of this idealized discontinuous current distribution for nearly spherical plasmas with a close fitting conducting shell. We consider incompletely relaxed current profiles where $\lambda \sim \tanh(b\psi/\psi_{max})$. The current smoothing parameter b controls the width of the region near the edge of the plasma in which the current falls to zero. We calculate the growth rates of n = 1 and n = 2 modes as a function of b and the oblateness ε (ε = polar radius/equatorial radius) and the wall separation. The region outside the plasma is treated as vacuum or as conducting plasma which produces line tying. The n = 1 growth rates are not significantly affected by current smoothing. They are minimum at an optimum oblateness of about $\varepsilon \approx .6$ and can then be stabilized by moving the wall in to $R_{wall}/R_{sep} \leqslant 1.2$ (with $Z_{wall}/R_{wall} \approx \varepsilon$) or $R_{wall}/R_{sep} \leqslant 1.5$ if there is line tying. The n = 2 modes are not greatly affected by oblateness and are stable if $b \gtrsim 5$ or $q_{axis} \gtrsim .6$ even if the wall is quite far away ($R_{wall}/R_{sep} > 2$). Thus, an excessively smooth current profile, with a large flux hole, destabilizes n = 2 modes because the q value is too low.

*Work supported by Department of Energy.

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1E21

QUASISTATIC EVOLUTION OF COMPACT TOROIDS*

A. G. Sgro, R. L. Spencer, and C. Lilliequist

Los Alamos National Laboratory

Los Alamos, New Mexico 87545

The quasistatic evolution of a gun injected compact torus (CT) is simulated with a 1-1/2D transport code. The initial configuration, consistent with experimental data just after formation of the CT, is the lowest energy force-free state. We compute the evolution and decay of the CT and compare the results with experiments. The configuration evolves to a state in which the current is peaked on the magnetic axis.

*Work performed under the auspices of the USDOE.

1E22

SLOSHING ION DISTRIBUTIONS IN MFTF-B*

Marvin E. Rensink
Lawrence Livermore National Laboratory, University of California
Livermore, California 94550

Several MFTF-B design alternatives have been examined recently, with sloshing ions an essential feature of all of these designs. Microstability is the primary motivation for studying the form of the ion distribution function. We present some examples of sloshing ions in MFTF-B, mainly in the anchor cell, as computed by a bounce-average Fokker-Planck code. The following factors are shown to have a significant influence on the sloshing ions: beam injection geometry, beam species mix, ionization and charge-exchange processes, axial magnetic field and potential profiles, charge-exchange pump beams, and warm ion sources.

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FREE BOUNDARY STABILITY OF A FINITE-BETA, $\ell=1$ STELLARATOR

D.C. Barnes and J.R. Cary
Institute for Fusion Studies
University of Texas
Austin, Texas 78712

The ideal MHD stability of long-wavelength, free-boundary modes in a finite-β, straight, helical system is investigated using the constant plasma pressure, surface current model. The equilibrium and stability problems for arbitrary cross section, plasma β, helical wavelength, poloidal winding number ℓ, and axial current reduce to potential problems for the interior and exterior domains.

Following a procedure described earlier[1], these potential problems are solved by the introduction of an appropriate Green's function. In contrast to previous work, our calculations retain all effects of finite helical wavelength and axial wavenumber k, and are thus applicable to $\ell=1$ systems of arbitrary type.

A numerical algorithm based on appropriate surface coordinates and summation techniques has been implemented and results obtained for various helical systems. For long wavelength $\ell=3$ systems, previous results, indicating arbitrarily small critical β's for particular k values[2], are reproduced. The pessimistic predictions of previous asymptotic expansions of near circular $\ell=1$ systems are also confirmed.

For an $\ell=1$ systems with an axial current at the geometric axis, the results are qualitatively different. A plasma shape studied by Monticello, et.al[3], shows moderate critical β's. The eigenvalue, ω^2, is seen to increase with β in some regions of parameter space, giving a β limit determined only by equilibrium. Results for similar cross sections produced by consistent vacuum fields are also given.

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MORE ACCURATE PLASMA EQUILIBRIA FOR COMPACT-TORI AND AXISYMMETRIC TANDEMS*

B. McNamara and D. M. Whitney
Lawrence Livermore National Laboratory, University of California
Livermore, CA 94550

Field line coordinates are the natural system for solving equilibrium problems with steep pressure gradients or high mirror ratios. Spheromak equilibria have an O-point at the magnetic axis and an X-point on-axis at the separatrix; mirror-cusp configurations also have an X-point. These singularities require special treatment in computing the metric of the coordinate system.

Simple tests with Hill's vortex actually yielded the analytic solution when an analytic metric was used in a numerical solver. This stimulated a search for the optional numerical metric which, for these equilibria, amounts to choosing the optimal set of field lines.

The surface-averaged equilibrium equation is a second order, ordinary differential equation and a general transformation has been found which balances the numerical error in the mesh with the errors in the solution to yield a fourth-order accurate scheme!

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1E25

CAN STABLE, LINEAR RESISTIVE MODES GIVE DYNAMO ACTION?*

T. Hewitt, R. Keinigs, R. Nebel, and R. Gerwin
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

In the Los Alamos ZT-40 experiment the anomalously long time that it takes for the reversed toroidal field to decay indicates the presence of some form of dynamo. One explanation for this might be that the large-scale equilibrium field is supported against resistive diffusion through the presence of many small-scale, linearly stable modes. Within this scenario the temporal evolution of the mean field, $\underset{\sim}{B}_0(r,t)$, is governed by the modified resistive diffusion equation,

$$\frac{\partial \underset{\sim}{B}_0}{\partial t} + \underset{\sim}{\nabla}\times\left(\frac{c^2}{4\pi}\,\eta(r)\underset{\sim}{\nabla}\times\underset{\sim}{B}_0\right) = \underset{\sim}{\nabla}\times\langle\delta\underset{\sim}{v}(r,t)\times\delta\underset{\sim}{B}(\underset{\sim}{r},t)\rangle \quad ,$$

where $\eta(r)$ is the plasma resistivity, and the brackets, $\langle\ \rangle$, denote an averaging that eliminates all interactions except those between modes having opposite helicities. This generation term might result in either (or both) a reduced resistivity (β-effect) or a change in the magnetic topology (α-effect). In order to determine its effect on diffusion we are using a complex version of the Hewett-Freidberg resistive MHD stability code to search for linearly stable eigenfunctions (incompressible) that can contribute to this generation term. Preliminary results will be discussed.

*Work performed under the auspices of the USDOE.

ALFVEN RESONANCE HEATING OF SPHEROMAKS*

S. Riyopoulos and E. Ott
Laboratory for Plasma and Fusion Energy Studies
University of Maryland
College Park, Maryland 20742

As a simple model for the study of Alfvén resonance heating in spheromaks, we consider a force-free cylindrical equilibrium with zero toroidal B field at the cylinder edge. This model is relevant to the case where the spheromak has a large flux hole. Finite $k_\perp$ and ω/Ω_{ci} are included in the calculations. Asymptotic analysis[1,2] is used to describe the absorption physics in the region of resonance. It is found that this method is quite promising for heating in spheromak experiments.

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Poster

STOCHASTIC E × B PARTICLE MOTION DUE TO TWO ELECTROSTATIC WAVES*

R. G. Kleva and J. F. Drake
Laboratory for Plasma and Fusion Energy Studies
University of Maryland
College Park, Maryland 20742

The E × B motion of a particle in the two-dimensional potential

$$\phi(x,y,t) = A[\cos(x)\cos(y - \nu_1 t) + \varepsilon\cos(x + \pi/2)\cos(y - \nu_2 t)]$$

is studied numerically. In the presence of a single wave ($\varepsilon = 0$) the particle motion is constrained to lie on a surface of constant energy. The addition of a second wave with a phase velocity different from that of the first destroys this energy constant of the motion and leads to particle transport. Surfaces of section which describe the transition to stochasticity as a function of the relative amplitude ε, overall amplitude A, and the phase velocity difference $\nu_2 - \nu_1$, will be presented. For parameter regimes in which the stochasticity is widespread, a statistical analysis of an ensemble of particle trajectories demonstrates that the transport is diffusive and obeys statistics which are nearly Gaussian. In the case of an infinite spectrum of waves equally spaced in phase velocity, a mapping is obtained which also exhibits a transition to stochasticity.

*Work supported by Department of Energy.

Poster

SOME EFFECTS OF HOT ELECTRON STABILITY IN TANDEM MIRROR GEOMETRY*

D. E. Baldwin
Lawrence Livermore National Laboratory, University of California
Livermore, California 94550

Several results for the low frequency behavior of hot electrons in EBT have been extended to the anchors and thermal barriers of tandem mirrors. The condition for MHD behavior of the hot electrons is determined by the background pressure, as found by Van Dam and Lee[1] for EBT. The stability of a high frequency interchange mode near the precessional frequency of hot electrons in the negative curvature wells of EBT was found by Dominquez and Berk[2] to require a significant majority fraction of cold electrons. In a tandem mirror, hot electrons in such a well, even though satisfying the Dominquez-Berk condition, can be destabilized by coupling the existing negative energy wave to a positive energy shear Alfvén wave standing in the length of the central cell. To avoid such a mode requires exceeding the critical Van Dam-Lee core β-value for low frequency stability. Thus, an axisymmetric cell cannot, by itself, be stable to both modes and must rely for stability on another, good curvature, cell.

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NONLINEAR PRESSURE DRIVEN MODES AND POSSIBLE RELATIONSHIPS TO ENERGY CONTAINMENT IN THE RFP*

T. C. Hender and D. C. Robinson**
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

ABSTRACT

A primarily numerical investigation has been made for the nonlinear g mode in the Reverse Field Pinch, using a spectral Fourier harmonic code [1]. Both single and multiple helicity calculations have been performed.

The single helicity results for modes with poloidal mode number, M = 0 and for the M = 1 modes in the core indicate that whilst their velocity components readily saturate, the magnetic components continue to grow, far into the nonlinear regime. It is found that the inclusion of parallel thermal conductivity aids the saturation of the magnetic component.

The multiple helicity interaction between an M = 0 mode, and an M = 1 mode in the core has been examined. It is found that the M = 0 mode nonlinearly destabilizes the M = 1 mode, by a mode coupling process similar to that for the tearing mode [2].

The possible relationship between the nonlinear g mode activity and energy containment in the RFP has been investigated. Field line and guiding centre calculations show that for the level of magnetic fluctuations indicated by the nonlinear calculations ergodic field line behaviour occurs across a large portion of the pinches minor radius. Using the Rosenbluth and Rechester expressions for ergodic transport [3], scalings and actual energy containment times have been derived for the RFP. These are found to be in reasonable agreement with experimental RFP results.

Investigations are currently in progress using the CYL code [4] to extend the above studies to a fully 3 dimensional situation with the ergodic energy losses included and the dynamo effect [5] also implicitly included.

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**Culham Laboratory, Abingdon, England.

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POSTER

MHD TURBULENCE IN TOKAMAK PLASMAS

D. Biskamp and H. Welter

Max-Planck-Institut für Plasmaphysik, EURATOM-ASSOCIATION
D-8046 Garching, Germany

A plasma with a certain parallel current distribution gives rise to the generation of MHD turbulence owing to the simultaneous growth of low m number tearing modes of different helicity.[1] Since this process is now generally associated with the occurance of a disruption in a tokamak plasma, it is important to understand the turbulent transport processes that lead to rapid poloidal flux expulsion. A 3D code using the reduced equations in cylindrical geometry with Fourier analysis in the two periodic directions has been developed capable of treating the quasi steady turbulent state. It is noticed that even with as many as 500 Fourier modes appropriately chosen in mode number space only magnetic Reynold's numbers $S = v_A a/\eta < 10^3$ can be adequately described. For larger S dissipation at high mode numbers is insufficient to guaranty a unidirectional flow of the magnetic energy to large k. The same is true for the kinetic mode energy for viscous Reynold's numbers $R = v_A a/\mu > 10^3$. This suggests that other dissipation mechanisms should be effective, in particular perpendicular electron viscosity which is very efficient in absorbing energy at high mode numbers and dominates over resistivity for $\mu_{e\perp} \geqq 10^{-2}\, \eta$. Since not the fluctuating current density but its spatial gradients increase with increasing S, the main turbulent transport effect is an anomalous electron viscosity and not so much an anomalous resistivity. We also consider parallel electron viscosity. Though numerically $\mu_{e\parallel}$ is usually much larger than $\mu_{e\perp}$ its effect is weak since $\nabla_\parallel \cong o$ at the resonant surfaces of the modes.

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Application of Stellarator Expansion Techniques to Tokatron Configurations*

J. L. Johnson† and G. Anania
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

Investigation of three-dimensional configurations such as the tokatron[1] is difficult. Two major tools have been used to evaluate the efficacy of this device: modeling with a two-dimensional cylinder with the behavior at the ends ignored, and superposition of calculations of the vacuum fields associated with the helical conductors on the fields due to an assumed toroidal current distribution. The need for a self-consistent equilibrium calculation has been met by using a small-aspect-ratio modification[2] of the stellarator expansion. The magnetic field is modeled by a toroidal field, a vertical field, a multipolar field, and a mirror field (to provide closure at the top and bottom), all of which are externally imposed, and the self-consistent poloidal field created by the plasma current. Since this model has a small rotational transform, it cannot provide guidance concerning stability.[3] The model has been extended to the standard stellarator ordering by going to large aspect ratio, so that this problem can now be addressed.[4]

†On loan from Westinghouse Research and Development Center

*This work supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

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Poster Session [next to Johnson and Anania]

Electromagnetic Wave Generation in a Beam-Plasma System*

P. L. Pritchett and J. M. Dawson
Department of Physics, University of California
Los Angeles, California 90024 U.S.A.

Fluctuating ω_p emissions have been observed in tokamks which cannot readily be explained in terms of direct Cerenkov emission by relativistic runaway electrons. An alternative mechanism is the nonlinear conversion of enhanced electrostatic plasma oscillations to electromagnetic emission by scattering from thermal-level ion acoustic fluctuations.[1] If the details of this generation mechanism are understood, the observation of such radiation could serve as an important diagnostic of fusion and laboratory plasmas. Towards this end, we are performing a study of the interaction of an electron beam with a background plasma using a relativistic electromagnetic particle simulation code. The simulation involves a nonuniform system, and both periodic and finite geometries have been investigated. Strong electromagnetic radiation near the plasma frequency has been observed. In the periodic case higher frequencies are observed, and these correspond to excitation of the normal modes of the system. In the bounded case no higher frequency peaks have been detected. We are studying the efficiency of the generation mechanism and investigating a possible burst structure in the radiation. The simulation results will be compared with the laboratory beam-plasma experiment of Whelan and Stenzel.[2]

*Work supported by USDOE, NSF, and NASA.

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POSTER SESSION

DIFFUSION OF FUSION-PRODUCED PARTICLES DUE TO SHEAR ALFVÉN FLUCTUATIONS

F. Pegoraro† and L. Sugiyama
Massachusetts Insitute of Technology, Cambridge, MA 02139
†and Scuola Normale Superiore, Pisa, Italy

Shear Alfvén waves can interact resonantly with the high energy charged particles produced by fusion reactions, amplifying the waves and producing a quasilinear outward diffusion of the particles in a toroidal magnetic configuration.[1] A study of the time evolution of a single shear Alfvén wave packet shows that in most cases the resulting diffusion is not large enough to seriously affect confinement and thus the deposition of fusion energy. We model the presence of a thermal background of shear Alfvén waves in an igniting plasma (due, for example, to magnetic noise or turbulence) by a time sequence of randomly generated wave packets.[2] For values of the interchange/ballooning parameter $G \sim (L_c/2\pi)^2(\beta/r_pR_c)$ in the low β region stable to ballooning modes the quasilinear diffusion is small. For values of G in the finite β or second stable region the diffusion is greater, though not excessive, especially near the stability boundary. The existence of dissipative processes may limit the actual diffusion in this region.

Work supported in part by the U.S. Department of Energy

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Nonlinear Gyrokinetic Equations for Low-Frequency Electromagnetic Waves in General Plasma Equilibria*

E. A. Frieman† and Liu Chen
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

A nonlinear gyrokinetic formalism for low-frequency (less than the cyclotron frequency) microscopic electromagnetic perturbations in general magnetic field configurations is developed. The nonlinear equations thus derived are valid in the strong-turbulence regime and contain effects due to finite Larmor radius, plasma inhomogeneities, and magnetic field geometries. The specific case of axisymmetric tokamaks is then considered, and a model nonlinear equation is derived for electrostatic drift waves. Also, applying the formalism to the shear Alfvén wave heating scheme, it is found that nonlinear ion Landau damping of kinetic shear-Alfvén waves is modified, both qualitatively and quantitatively, by the diamagnetic drift effects. In particular, wave energy is found to cascade in wavenumber instead of frequency.

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†Present address: Science Application, Inc., La Jolla, CA 92038 and University of California, San Diego, CA 92092.

Oral Session

POSTER SESSION

TRANSPORT COEFFICIENTS OF TRACE HEAVY IMPURITY IONS IN A ROTATING PLASMA*

S. K. Wong, M. Rosenberg, and K. H. Burrell
General Atomic Company
San Diego, California

ABSTRACT

It was recently demonstrated[1] in a fluid model that the inclusion of inertial forces arising from plasma rotation in tokamaks leads to expressions for impurity cross field fluxes which predict greater inward migration for counter-rotation than co-rotation. A kinetic theory of transport extending the usual neoclassical theory to deal with larger rotation has also been formulated.[2] The fluid results can be obtained with more accuracy and completeness from the kinetic theory, which we present in this paper.

We have both numerically and analytically solved the kinetic equation for a trace heavy impurity ion species in the plateau to Pfirsch-Schlüter regime. Although plasma rotation explicitly enters, the results actually encompass realistic cases of neoclassical impurity transport when $\sqrt{(m_I/m_i)}(\rho_{\theta i}/r_n)$ is no longer small,[3] which is a relevant plasma regime seldom treated. Application of the results to the simulation of impurity injection experiments in ISX-B[4] will also be discussed.

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*Work supported by Department of Energy Contract DE-AT03-76ET51011

MULTI-REGION BOUNCE-AVERAGED FOKKER-PLANCK CODE AND STUDY OF THERMAL BARRIER IN A TANDEM MIRROR*

Y. Matsuda and J. J. Stewart

We have developed a new multi-region bounce-averaged Fokker-Planck code using the Galerkin finite-element method for studying the behavior of trapped particles in general magnetic and potential wells. This work was motivated by the need to study physics of the thermal barrier generated by ECRH in a tandem mirror such as TMX-Upgrade and MFTF-B at LLNL.

In a thermal barrier region there typically exist three different groups of trapped electrons; they are magnetically trapped hot electrons (μ-trapped), potentially-trapped warm electrons (Φ-trapped), and those electrons which are trapped by the potential on one side and the magnetic field on the other (Yushmanov-trapped). An important feature of this configuration is that for a given energy, ε, and a magnetic moment, μ, there may exist two spatially separated electrons, one Φ-trapped and the other Yushmanov-trapped. So, in the part of (ε, μ) phase space one has to introduce overlapping multiple regions which are connected by a flux continuity condition. These three groups of electrons interact simultaneously through the Coulomb collisions.

One of the applications of the code is the study of ECRH-trapping of the electrons flowing out of the central cell. In a TMX-Upgrade type of situation, the code has shown a significant enhancement of the trapping rate when the Yushmanov-trapped electrons are included. Details of this result, other applications, and the code will be reported.

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"GENERATION OF HYBRID FIELD-REVERSED EQUILITORIA" *

E. C. Morse and Z. Mikic
Department of Nuclear Engineering
University of California
Berkeley, California 94720

We have generated axisymmetric field-reversed equilibria with finite toroidal magnetic field, for use in our 3-D linearized hybrid stability code, an extended version of the code RINGHYBRID (1), to study the linear stability of compact toroids with finite toroidal magnetic field (e.g., Spheromak).

The electrons are treated as a finite-pressure fluid, while the Vlasov ions have an exponential rigid-rotor distribution function (i.e., an isotropic Maxwellian in the rotating frame). Thus, the ions contribute to the poloidal magnetic field only, while the electrons contribute to both the poloidal and toroidal fields.

The equilibrium is obtained by numerical solution of a non-linear Grad-Shafranov -type equation. The solution method is a modification of one used by Friedman (2).

The equilibrium will be used in our stability code to study the effect of finite ion-gyroradius effects, in exploring the β-limit in Spheromak, and in the study of pressure driven modes.

*Work supported by the U.S. Department of Energy

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(2) A. Friedman, First Quarterly Progress Report (Jan. 1 - March 30, 1980), Electronics Research Laboratory, University of California, Berkeley.

1E38

Particle Transport in Reversed Field Pinches

C. E. Seyler
Laboratory of Plasma Studies, Cornell University, Ithaca, NY 14853

This work is strongly motivated by the intriguing behavior of the ZT-40 Reversed Field Pinch (RFP) experiment at Los Alamos. The experimental observations which have influenced the development of the proposed particle transport model are the following: (1) In the initial phase of the discharge there are substantial transient magnetic field fluctuations. (2) Rapid particle loss is observed which slows to (3) moderate loss in the plateau phase in which (4) there is a reduction of magnetic fluctuations until (5) there is an enhancement of fluctuations in the termination phase and (6) finally an abrupt quenching of the discharge.

Accepting this simplified description of ZT-40 behavior, we believe there is a relatively simple self-consistent model which can account for all six of the aforementioned points. A key experimental clue is that in the plateau regime, the density is consistent with the parallel electron current drift velocity being approximately the Alfvén velocity. This suggests a possible electron drift-Alfvén wave interaction mechanism.

We propose a guiding center model for particle diffusion, which is based upon irreversible $\nabla\phi_1 \times B_0$ drifts occurring as the result of the self-consistent electrostatic potential due to the guiding center electron response to Alfvén wave fluctuations. We show that the resulting test particle diffusion coefficient predicts that the rate of particle loss, in the initial startup phase, is consistent with the observed amplitude of the damped initial transient fluctuations. We also show that the diffusion coefficient approaches a minimum, for fixed fluctuation amplitudes, when the parallel drift velocity is of the order of the Alfvén velocity. This is consistent with the rate of particle loss during the plateau phase. And finally we argue that near the termination phase the enhanced magnetic fluctuations are due to resonantly driven Alfvén waves, when the drift velocity exceeds the Alfvén velocity. This suggests from the dependence of the diffusion coefficient upon the density that increasing fluctuations drive particle loss and a subsequent increase in drift velocity further increasing transport, finally culminating in explosive pumpout and thus a quenching of the discharge. In this model, improved particle confinement could be achieved by substantially reducing the initial startup fluctuations, whatever their source.

This work supported by U.S. Department of Energy Contract DE-AS02-76ET53065.

1E39

POSTER SESSION

LOW-q_ℓ DISCHARGES AND KINK INSTABILITY*

L. C. Bernard, F. J. Helton, J. K. Lee, and R. W. Moore
General Atomic Company
San Diego, California

ABSTRACT

Tokamak discharges with a low q_ℓ (the safety factor at the limiter) are of great interest to achieve high β values. In a recent series of experiments, the Doublet III tokamak was successfully operated with $q_\ell \sim 2$. It was observed that the probability of a discharge terminating with a major disruption increased as q_ℓ decreased from 4 to 2. However, when q_ℓ became less than a threshold value close to 2, the discharge always disrupted. A numerical study shows that observations are consistent with the onset of an ideal-MHD free surface kink instability, n=1,m=2 (n and m are the toroidal and poloidal mode numbers, respectively). The GATO code is used to perform the stability analysis on numerical equilibria which model the experiment (aspect ratio 3, circular shape, $\beta_p \sim 0.1$). The effect of the current profile on the q_ℓ-threshold for the onset of the kink instability will be discussed.

*Work supported by Department of Energy Contract DE-AT03-76ET51011

1E40

Abstract Submittal for the 1982 Sherwood Meeting,
Annual Controlled Fusion Theory Conference,
Santa Fe, New Mexico, 25-28 April 1982

A Data File of Iron Ion Excitation Collision Strengths. J. B. MANN Los Alamos National Laboratory--The excitation of iron ions by electron impact in the fusion reactor plasmas is of importance for radiation power loss and diagnostic studies. Many calculations have been carried out for 13 ion stages of iron by a distorted wave method. Much of the resulting data will be published elsewhere, but data for transitions between individual levels are too voluminous for easy publication. A data file is being established in the FILEM system of the A7600 computer in the National MFE Computer Center, at Lawrence Livermore National Laboratory. Details of the file contents and access will be presented.

Prefer Poster Session

Joseph B Mann

Joseph B. Mann
Los Alamos National Laboratory
Los Alamos, NM 87545

POSTER SESSION

A LINEAR MODEL FOR THE TEARING MODE OF A TOKAMAK PLASMA WITH FLOW AND A "RESISTIVE WALL" BOUNDARY CONDITION*

Torkil H. Jensen
General Atomic Company
San Diego, California

ABSTRACT

The tearing mode of a Tokamak plasma without flow may be stabilized by the presence of a conducting wall surrounding the plasma. In case the wall has a finite resistivity, its presence does not affect stability, only growth rates. If, however the plasma has a flow relative to the resistive wall, both stability and growth rates may be affected. For the cylindrical, circular cross section Tokamak the problem is formulated as a complex eigenvalue problem, with a complex eigenvalue Δ', which in the limit of vanishing flow becomes identical to the usual "delta prime". The real part of Δ' describes as usual the power absorbed at the singular surface while the imaginary part describes absorption of momentum. It is found that for a plasma with shearless flow, a resistive wall has a stabilizing effect which even for relatively small flow velocities approaches that of a wall of infinite conductivity. Shear flow is found inherently destabilizing, but important only for very large flow velocities.

*Work supported by Department of Energy Contract DE-AT03-76ET51011

"Ensemble Modes" in the Nonadiabatic Behaviour of Particles in Inhomogeneous Magnetic Fields

R.K. Varma
Physical Research Laboratory
Navrangpura, Ahmedabad 380 009
INDIA

Abstract

A theory is presented which describes the nonadiabatic behaviour in the neighbourhood of adiabatic motion, of an ensemble of charged particles in an inhomogeneous magnetic field. The ensemble is constructed in a manner that it corresponds to an experimental situation where the particles are injected into a mirror trap with the same specified values of the total energy and the magnetic moment invariant, or the first adiabatic invariant μ, but different values of the Larmor phase at a given spatial position.

It is found, interesting enough, that the ensemble possesses a set of normal modes in terms of which the nonadiabatic behaviour of the ensemble of particles can be described. These modes are designated here as the "ensemble modes" and are to be distinguished from the collective modes since the particle density is assumed to be so low that the inter-particle interactions are negligible. These "ensemble modes" are described by a set of Schrodinger-like equations for a set of probability amplitudes $\Psi(n)$, $n = 1,2,3$, where μ/n appear in the role of $\hbar$ and the adiabatic potential $\mu\Omega$ in the place of potential in the Schrodinger equation of quantum mechanics. An experimental verification of the existence of the "ensemble modes" has indeed been found recently in the observation of multiple life times in the nonadiabatic decay of particles from axisymmetric magnetic mirror traps.

1E43

Stability Studies Using the Stellarator Expansion*

G. Anania and J. L. Johnson†
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

Recent interest in stellarators arises from their apparent high beta values, obtained with local stability criteria.[1] Kink modes are not considered because stellarators have no net current. A stability code is developed to investigate the effect of Pfirsch-Schlüter current on these modes. The Lagrangian for perturbations about an equilibrium is reduced to a functional of a single independent variable with the stellarator expansion.[2] We have modified the PEST-2 stability code[3] to incorporate this formalism. Using the proper kinetic energy normalization makes the eigenfunctions and growth rates correctly describe the expected linear behavior of the perturbations. Code validation studies are in progress and will be reported. Application to the study of modular stellarators,[4] existing devices including Heliotron E, and tokatrons[5] is forthcoming.

†On loan from Westinghouse Research and Development Center.

*This work supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

1. L. M. Kovriznykh and S. V. Shchepetov, European Plasma Physics Meeting (Moscow, September, 1981) paper E-11.
2. J. L. Johnson and J. M. Greene, Phys. Fluids 4, 1417 (1961).
3. R. C. Grimm, R. L. Dewar, and J. Manickam, Princeton University Report PPL-1885 (February, 1982).
4. G. Anania, J. L. Johnson, and K. E. Weimer, Bull. Am. Phys. Soc. 26, 956 (1981).
5. J. L. Johnson and G. Anania, these proceedings.

Poster Session [next to Anania and Johnson]

1E44

A CLASS OF TOROIDAL STELLARATOR EQUILIBRIA

J.P. Freidberg and P. Rosenau
Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

We investigate a class of toroidal MHD stellarator equilibria. As in conventional tokamaks, our expansion procedure is based on $\beta \sim (a/R)^2$ and leads to an entirely analytic theory. In particular we obtain analytic formulae for the plasma shift and the toroidal force balance. Within the frame of this theory, it is possible to proceed smoothly from a pure tokamak, through arbitrary hybrids, to the pure stellarator.

One of the theory goals is to address the problem of position control in stellarators by means of a vertical field. The following apparent paradox arises: on one hand, as is well known, the application of a vertical field shifts the vacuum flux surfaces of a stellarator; on the other hand, in a <u>current free</u> tokamak there is no net $\vec{J} \times \vec{B}_{vert}$ body force as in the tokamak. Thus arises the paradox: how can a vertical field which produces no net body force produce a shift in the flux surfaces? This paradox has been resolved and will be discussed at the meeting.

Review of Some Topics in Turbulence Theory

R. Kraichnan

Dubin, NH 03444

The following topics in present-day theory all are relevant to turbulence shaped by strong magnetic fields: instability and the paths to turbulence; competition in computability between the raw amplitude equations and equations for statistical averages; inferences from nondissipative absolute equilibrium models; divergence of renormalized perturbation theory and the construction of convergent approximations; survival of invariants, conservation properties, and realizability properties under statistical approximation; error estimation.

The emphasis in this talk will be on fundamental criteria for constructing and judging approximate treatments of strongly turbulent states.

On the Relation Between "Mixing Length" and "Direct Interaction Approximation" Theories of Turbulence

R. N. Sudan and D. Pfirsch*

Laboratory of Plasma Studies, Cornell University, Ithaca, NY 14853

A systematic procedure is outlined for deriving the Kolmogoroff-Heisenberg type conservation equations[1] in k-space for cascading power transfer, from the "Direct Interaction Approximation" equations of strong turbulence for a large class of plasma and fluid systems. The simplification afforded by this technique enables the solution of a wide class of problems for which the DIA equations are very unwieldy. This method has recently been applied to deriving the spectrum of magnetic field fluctuations in a very high β turbulent conducting fluid.[2]

1. W. Heisenberg, Zs. f. Physik 124, 628 (1948).
2. R. N. Sudan and R. M. Kulsrud, Cornell University Laboratory of Plasma Studies Report 300 (1982).

*Permanent address: Max-Planck-Institut für Plasmaphysik, 8046 Garching Bei München, West Germany.

ORAL PRESENTATION

NUMERICAL STUDY OF DRIFT WAVE TURBULENCE WITH SIMPLE MODELS FOR NONLINEAR WAVE-WAVE COUPLING*

R. E. Waltz
General Atomic Company
San Diego, California

ABSTRACT

Fixed wave number ($k_\perp$) scattering experiments on tokamaks have shown density fluctuation ($\tilde{n}/n_0$) having a broad drift wave ($\omega \sim \omega_*$) spectrum with $\Delta\omega/\omega \sim O(1)$. This appears to indicate a strong turbulent state with unstable modes rapidly decorrelated by their nonlinear wave-wave coupling to stable modes. Motivated by these experiments, a study of 2D (k_x,k_y) stationary homogeneous turbulence for nonlinear models of the type

$$d\tilde{\Phi}_k/dt = -i\omega_k\tilde{\Phi}_k + \gamma_k\tilde{\Phi}_k + \sum_{k_1k_2} \delta(k-k_1-k_2)\, V_{kk_1k_2}\, \tilde{\Phi}_{k_1}\, \tilde{\Phi}_{k_2}$$

is presented. The electrons are characterized by fast parallel field motion giving a linear Boltzmann response $\tilde{n}_k/n_0 = e\tilde{\Phi}_k/T_e\,(1 - i\delta_k)$. The ions are treated with cold fluid cross field dynamics which include both nonlinear polarization drifts and nonlinear EXB motions (from $\delta_k \neq 0$). Simple model functions for δ_k are used to drive unstable modes ($\gamma_k > 0$) in the range $k_\perp\rho_s < 1$ and shear damping is included ad hoc. In general it is found that the simple models with reasonable γ values give the experimental turbulence levels $\tilde{n}/n_0 = e\tilde{\Phi}/T_e \sim O(3\rho_s/L_n)$, transport coefficients $D \sim O(\rho_s{}^2 c_s/L_n)$, and decorrelation rates $\Delta\omega \sim O(\omega_*)$ within factors of 2. In addition, a number of tests for the mathematical and numerical descriptions of the turbulence are provided. The exact solutions for the wave spectrum $I_{k,\omega} = |\tilde{\Phi}_{k,\omega}|^2$ are found by time averaging over the time dependent solutions of $\Phi_k(t)$ followed into a stationary stochastic state. Also, equations for an approximate weak coupling theory that directly give the integrals I_k, frequency shifts $\delta\tilde{\omega}_k$, and decorrelation rates $\Delta\omega_k$ are solved. With computing efficiencies 10 to 100 times faster, this approach provides a good description of the exact solutions within factors of 2. Saturation with increasing number of modes is generally assured at 31×31 (k_x,k_y) modes. Studies with more elaborate physical models are in progress.

*Work supported by Department of Energy Contract DE-AT03-76ET51011

Resistive Pressure Driven Modes in High β Tokamaks*

B. A. Carreras, J. A. Holmes, W. A. Cooper,
H. R. Hicks, and V. E. Lynch
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

and

P. H. Diamond and P. L. Similon
Institute for Fusion Studies
Austin, Texas 78712

ABSTRACT

Resistive MHD calculations, based on the reduced MHD equations [1], show that at finite β there are unstable resistive pressure driven modes below the threshold of ideal instability. Their linear growth rates scale as $(n\varepsilon\beta_p)^{2/3}\ \eta^{1/3}$, where n is the toroidal mode number, ε the inverse aspect ratio and η the resistivity. These modes, even for very low n values, are described well by the asymptotic equation for large n.

These modes saturate at very low level for low β_p equilibria. However, with increasing β_p they become more important. Their n spectrum is concentrated at low mode number and is broad. An analytic model has been developed to study their nonlinear saturation. The model indicates that the level of saturation of kinetic energy scales like $(\varepsilon\beta_p)^{5/3}\ \eta^{4/3}$. These scalings have been confirmed by numerical results. Fluctuation spectra similar to those calculated have been observed in ISX-B at high β_p. The induced electron anomalous losses have been estimated, giving a diffusion coefficient which scales like $(\varepsilon\beta_p)^2$.

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*Research sponsored by the Office of Fusion Energy, Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

[1] H. R. Strauss, Phys. Fluids 20, 1354 (1977).

ORAL

MHD Fluctuations of Compressible Plasmas

H. A. Rose
Los Alamos National Laboratory

and

E. Hameiri and K. Riedel
Courant Institute of Mathematical Sciences
New York University

ABSTRACT

Plasma parameters generally fluctuate, especially in reversed-field devices which do not have a strong stabilizing toroidal magnetic field. The presence of fluctuations may give rise to enhanced transport. We have constructed a model of fluctuating fluid plasmas based on replacing the usual equations by their finite-difference approximation over a fixed numerical grid, and writing evolution equations for grid valued functions. After discretizing the equations in conservation form we prove a Liouville theorem for this system and show that it conserves mass, momentum, energy, and magnetic fluxes, as well as a discrete form of the helicity $\int \underset{\sim}{A} \cdot \underset{\sim}{B}$ ($\underset{\sim}{B} = \mathrm{curl}\underset{\sim}{A}$). A Gibbs probability distribution is then used to determine the fluctuations. This construction can be carried out in a realistic plasma configuration of a torus with walls, and will enable comparison with experimental results.

In order to facilitate a comparison with Landau's linear theory of fluid fluctuations[1], we derive the equal time probability distribution of that theory from a maximum entropy principle subject to the usual conservation laws. We then find agreement in the low temperature limit for some fluctuating quantities but perhaps not all. Further study is under way.

1. L. Landau and E. Lifshitz, Fluid Mechanics (Pergamon Press, 1959), Chap. 17.

This work was supported by the U.S. Department of Energy Contract No. DE-AC02-76ER03077 and W-7405-ENG-36 and the Air Force Office of Scientific Research Contract No. AFOSR-81-0020.

Oral Presentation

TEARING MODES IN TOROIDAL GEOMETRY*

J. F. Drake, T. M. Antonsen, Jr., and Y. C. Lee
Laboratory for Plasma and Fusion Energy Studies
University of Maryland
College Park, Maryland 20742

The tearing layer equations for low m modes in toroidal geometry are derived from the Braginskii fluid equations. The dynamics of the tearing layer are described by four coupled, second order, differential equations; the dependent variables being the stream function, the magnetic flux function, the pressure, and the electron temperature. Included in the equations are both parallel and perpendicular electron transport and all relevant diamagnetic effects. The equations are valid for arbitrary β and aspect ratio and reduce to the previously derived slab[1] and toroidal equations[2] in the appropriate limits. This system will be investigated to determine if the stabilization of tearing modes at high values of $\beta L_s^2/r_n^2$ found in slab geometry persists in toroidal geometry.

*Work supported by the Department of Energy.

[1] A. B. Hassam, Phys. Fluids 23, 2493 (1980).
[2] A. H. Glasser, J. M. Greene, J. L. Johnson, Phys. Fluids 18, 875 (1975).
[3] J. F. Drake, T. M. Antonsen, Jr., A. B. Hassam, and N. T. Gladd, to be published.

Oral

Unstable Continua in Ideal MHD*

Robert L. Dewar
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

The spectrum of unstable short wavelength internal modes (ballooning modes) on general toroidal static equilibria can be analyzed by a WKB technique. The ray tracing problem can be reduced to a non-Hamiltonian system of equations in a three-dimensional phase space. The rays fall into three main classes: those which cover invariant tori ergodically, those which are attracted to stable periodic orbits (cycles), and those which are attracted to stable fixed points. The ergodic case is excluded by the quantization condition, and we interpret the attracting cycles and fixed points as continuum modes. They reduce in the axisymmetric limit to discrete (but degenerate) eigenvalues and the $n = \infty$ accumulation point, respectively. These phenomena have been investigated numerically using a model dispersion relation for a tokamak with $n = 5$ toroidal ripple. It is found that the bands corresponding to the stable cycles are extremely narrow, but that the accumulation point broadens out into a wide continuum band for moderate values of ripple.

*This work supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

Poster Session

EQUILIBRIUM STUDIES FOR ATF-1 CONFIGURATIONS*

L. Garcia, B. A. Carreras, J. H. Harris,
and V. E. Lynch

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

We have studied the equilibrium properties of different stellarator magnetic field configurations using a modified version of Chodura-Schlüter code.[1] The vacuum magnetic field configurations are generated by filaments representing the coils.[2] The initial pressure profiles are constructed such that the pressure is constant on vacuum magnetic surfaces.

Optimization studies are in progress for different types of configurations. Torsatrons with continuous coil configurations have shown favorable equilibrium properties. We have found equilibria with $\langle\beta\rangle \sim 4\%$ with reasonable magnetic surfaces for this type of configurations.

Studies are continuing for modular stellarators, modular torsatrons, snake stellarators, and other configurations. Results will be presented at the meeting.

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*Research sponsored by the Office of Fusion Energy OER, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

[1]R. Chodura and A. Schlüter, J. Comp. Phys. 41, 68 (1981).

[2]V. E. Lynch, R. H. Fowler, R. A. Dory, J. H. Harris, J. F. Lyon, T. C. Jernigan, and J. A. Rome, Bull. Am. Phys. Soc. 26, 891 (1981).

POSTER SESSION

A PROPOSED β LIMIT TEST USING SHAPE CONTROL*

R. L. Miller
General Atomic Company
San Diego, California

ABSTRACT

Although a β limit has been observed in ISX-B it appears to exceed the ballooning mode limit predicted by ideal MHD theory. So the question naturally arises if the observed β limit is due to MHD effects at all. Here we attempt to help answer that question by searching for two equilibria which could be produced in beam-heated Doublet III. They should have different shapes which would lead to significantly different theoretical β limits (preferably a factor of two). Since experimental control is limited, it is also necessary to show that modest changes in the shape or current profile do not strongly affect the stability of the equilibria. If different β saturation levels are then observed for the two shapes in an experiment, this could be interpreted as evidence of ballooning mode effects.

*Work supported by Department of Energy Contract DE-AT03-76ET51011

Ballooning Modes and the Continuous Spectrum in MHD

E. Hameiri and P. Laurence
Courant Institute of Mathematical Sciences
New York University

ABSTRACT

Ballooning modes in general MHD configurations are treated rigorously as part of the continuous spectrum[1] and without the use of a WKB representation. They arise from waves propagating along field lines and are determined by a 4th order system of ODE's as derived by Dewar and Glasser[2] for the static equilibrium case. The correct boundary conditions on the infinite field lines fall out automatically in our treatment. The presence of flow sometimes, but not always, eliminates the ballooning spectrum. When this part of the spectrum survives the existence of flow, it reflects not simply bad curvature but also centrifugal force effects. The special case of a rigidly rotating axisymmetric mirror configuration is investigated closely and we show that stability to ballooning modes is necessary and sufficient for global stability.

We also present a general mathematical proof that for axisymmetric configurations, the ballooning spectrum consists of a dense set of eigenvalues. It then appears that when mass flow eliminates this spectrum, it merely indicates a failure of unstable modes to accumulate (as they can be located anywhere in the complex ω plane) rather than a stabilization effect.

1. E. Hameiri, Sherwood Meeting, Mount Pocono (1979), paper 2B21.

2. R. Dewar and A. Glasser, Ballooning Mode Spectrum in General Toroidal Systems. (Preprint)

This work was supported by the U.S. Department of Energy Contract No. DE-AC02-76ER03077.

Oral presentation

A Study of Lower Hybrid Ray Bundles with LHTOR*

A. H. Glasser and G. J. Kuperberg, Auburn University

The significance of ray trajectories in the study of wave propagation is that they form channels through which the wave energy flows. The simultaneous behavior of a bundle of rays is therefore more meaningful than the behavior of a single ray. The difficulty of the problem is enhanced by the high degree of complexity of the results, especially in the case of lower hybrid waves in toroidal geometry in the presence of magnetized ion effects. This problem is treated by means of newly developed computer graphic techniques. The results show strong focussing of the rays near the edge of the plasma where the waves are injected, followed by strong defocussing near the end of the trajectory, where they are absorbed. This behavior has important consequences for nonlinear phonomena and for the mechanics of energy conversion and absorption. Numerous case studies will be presented.

*Work supported by Department of Energy Contract #DEAC0181ER53121

MHD EQUILIBRIUM WITH NON-IDEAL BOUNDARY CONDITIONS[†]

David Montgomery, University of Maryland[*]
George Vahala, College of William and Mary
Linda Vahala, Old Dominion University

The boundary conditions for a viscous, resistive magnetofluid at a rigid, perfectly-conducting boundary are $\mathbf{v} = 0$, $\hat{n}\cdot\mathbf{B} = 0$ and $\hat{n} \times \mathbf{j} = \hat{n} \times (\nabla \times \mathbf{B}) = 0$, where $\mathbf{B}$ is the magnetic field, $\mathbf{j}$ is the current density, $\mathbf{v}$ is the fluid velocity and $\hat{n}$ is the unit normal. The third condition (which follows from the vanishing of the tangential electric field) has implications for MHD equilibria, often discussed only in terms of ideal boundary conditions. If the first two terms in $\partial\mathbf{B}/\partial t = \nabla \times (\mathbf{v} \times \mathbf{B}) - \eta\nabla \times \mathbf{j}$ vanish (where η = resistivity), then so must $\nabla \times \mathbf{j}$. This implies $\mathbf{j}$ may be written as $\mathbf{j} = \nabla\phi_J$, where, since $\nabla\cdot\mathbf{j} = 0$, ϕ_J obeys Laplace's equation, $\nabla^2\phi_J = 0$. A solution of Laplace's equation with vanishing tangential derivatives at the boundary is exceedingly restrictive: e.g., there is no axisymmetric solution inside an infinitely-long, right, circular cylinder which is independent of the axial coordinate z. A cut in the boundary is required (as is common practice experimentally) in order to have electric fields that penetrate and drive currents. Current may flow normally into the conducting wall if the conductivity does not vanish there. The region of finite current is confined to a few tube radii from the cut (in z), if the conducting tubes on either side of a cut are held at different potentials. A cut spacing small compared to tube radius seems requisite for current profiles as commonly given. Boundary layers in the current near the boundary may be indicated for conductivities which remain finite near the wall. Numerical solutions of the relevant 2D magnetostatics problem are exhibited.

[*]Permanent address: College of William and Mary

[†]Work supported by D.O.E. and N.A.S.A.

SLOWING DOWN OF ION RINGS*

C. B. Ruchti and R. V. Lovelace, Cornell University

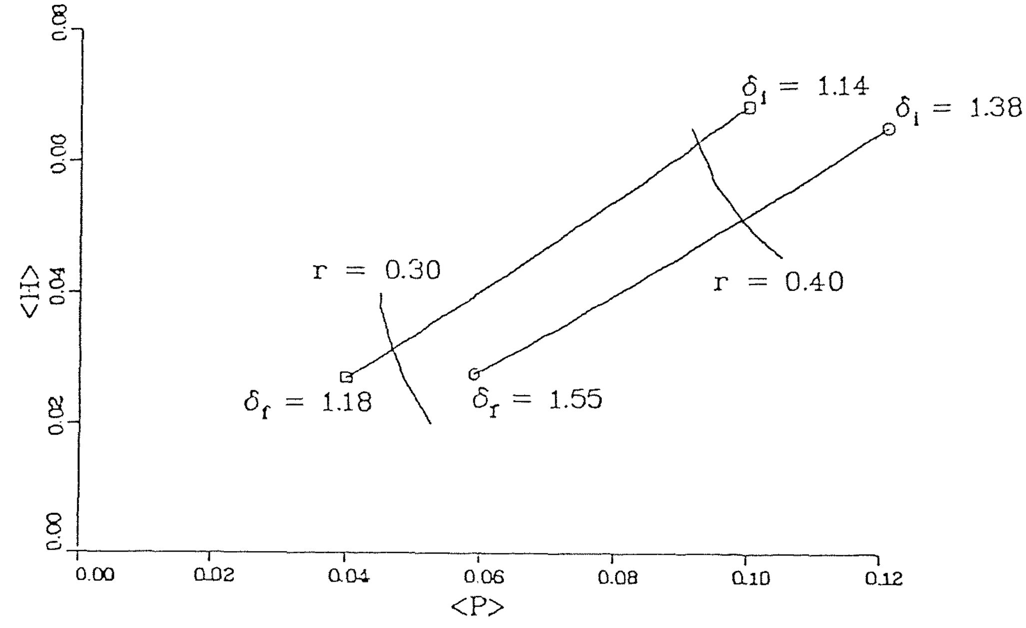
We consider large orbit ion rings immersed in a dense, cold background plasma and derive a kinetic equation including the influence of collisions with the background electrons. The distribution function depends on H (total energy) and P(canonical angular momentum). Using the adiabatic invariant I(P,H) (Lovelace[1]) we find:

$$\frac{\partial f}{\partial t} = \frac{1}{T} \left(A \left[2H - \langle mrv_\theta \rangle \langle v_\theta / r \rangle \right] \frac{\partial f}{\partial I} + \langle mrv_\theta \rangle \frac{\partial f}{\partial P} \right)$$

where A is the cross sectional area of the ring. We assume a double δ distribution $f = k\,\delta(H-\langle H\rangle)\,\delta(P-\langle P\rangle)$ and solve the equation numerically, computing a sequence of equilibria (Larrabee[2]) to determine the coefficients $\langle mrv_\theta\rangle$ and $\langle v_\theta/r\rangle$. The resulting slowing down tracks in the $(\langle H\rangle,\langle P\rangle)$ plane and contour lines of constant major radius are shown in the figure below. The equilibria along the upper track are more elongated in z direction ($\Delta z/r \sim 3$) and show an approximately constant field reversal. Along the lower track, however, the rings are compacter and show a gradual increase in the field reversal (δ_i=1.38 to δ_f=1.55).

*Work supported by DOE contract DE-AS02-76ET53017.

[1] R. V. Lovelace, Phys. Fluids 19, 723 (1976).
[2] D. A. Larrabee and R. V. Lovelace, Phys. Fluids (1982).



BOUNCE-AVERAGED FOKKER-PLANCK/QUASILINEAR DIFFUSION CALCULATIONS IN TOROIDAL DEVICES*

G. Kerbel and M. G. McCoy
National Magnetic Fusion Energy Computer Center
Lawrence Livermore National Laboratory
Livermore, California

We have generalized our multispecies non-linear Fokker-Planck package to allow the bounce averaging of both Coulomb collision and RF-induced quasilinear diffusion operators within the small banana width approximation. Since trapped particle effects are now evaluated by the code, a more accurate accounting of various RF heating schemes (e.g., minority species heating) on current drive in steady state toroidal devices is possible. The multispecies nature of the package allows examination of neutral beam Ohkawa current drive and reactivity enhancement due to ICRH.

*Work performed under the auspecies of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

Prefer Poster Session

2D9

RELATIVISTIC EFFECTS ON THE WHISTLER MODE IN EBT*

P. N. Guzdar
Laboratory for Plasma and Fusion Energy Studies
University of Maryland
College Park, Maryland 20742

The stability of the hot electron ring to the whistler instability has been recently investigated.[1] The anisotropy of the hot electrons was found to destabilize the mode via the multiple resonances of the type $m\omega_b = \omega - \Omega_e$, where m is a positive integer, ω_b is the hot electron bounce frequency, ω the wave frequency, and Ω_e the electron gyrofrequency. In the present calculation the relativistic modifications of the bounce resonances have been studied. It is found that although the relativistic effects tend to stabilize the mode, the reduced growth rates are substantial.

*Work supported by the Department of Energy.

[1]P. N. Guzdar and R. Marchand, "Whistler Instability in the Elmo Bumpy Torus," U. of Md. Report PL #80-046 (to appear in Phys. Fluids).

Poster

ORAL PRESENTATION

MINIMUM ENERGY STATES WITH FINITE PRESSURE IN CURRENT CARRYING PLASMAS*

J. Y. Hsu and J. K. Lee
General Atomic Company
San Diego, California

ABSTRACT

Using magnetic helicity $H = \int \vec{A}\cdot\vec{B}d\tau$ and poloidal flux $\chi = \int A_z d\tau$ as constants of motion, Taylor's force free states are generalized to include the plasma pressure. The minimum energy states thus obtained are a subset of the ideal MHD equilibria satisfying

$$\vec{\nabla}p = \vec{j} \times B_o\hat{e}_z \quad , \qquad \vec{\nabla} \times \vec{b} = \lambda\vec{b} \quad . \tag{1}$$

Here $\vec{B} = B_o\hat{e}_z + \vec{b}$, with B_o the vacuum magnetic field assumed uniform in the cylindrical approximation, and λ the eigenvalue. The pinch stability condition becomes more stringent with finite pressure, and the high β_p tokamak regime connecting to the pinch regime smoothly, exhibits the parametric dependence for minor and major disruptions.

For the low β_p tokamak regime, the $\beta_p = 1$ limit in which $j_\theta = 0 = b_z$ such that

$$\frac{dp}{dr} = -j_z b_\theta = -\frac{b_\theta}{r}\frac{d}{dr} rb_\theta \tag{2}$$

is considered by adopting the trial function for the safety factor $q(r) = q_o + (q_\ell - q_o)(r/a)^\nu$ with ν the variational parameter. Imposing the constancy of the magnetic helicity $H = B\chi$, and solving p from Eq. (2), the energy contours plotted on the plane of $(\nu, z \equiv q_o/q_\ell)$ show that (i) local minimum energy states exist if $q_o/q_\ell < z_c = 0.04$, (ii) at constant ν (fixed profile), local minimum energy states also exist at $z < 0.2$. The absolute minimum energy state has $\nu\to\infty, z\to 0$ (an essential singularity) corresponding to skin current profile without plasma confinement.

*Work supported by Department of Energy Contract DE-AT03-76ET51011

2D11

KINETIC STABILITY OF REVERSED FIELD PINCHES*

J. P. Mondt and T. Hewitt

Coherent electromagnetic excitations, appearing just prior to termination and travelling with velocities exceeding the diamagnetic drift speed, have been identified experimentally in ZT-40. Presently an attempt is made to describe this phenomenon within the context of linear stability theory. To retain wave-particle resonance effects the ion Vlasov equation is approximated by the first two terms in a finite Larmor radius expansion. On the time scale of interest the electrons are highly collisional. Therefore, a fluid model with $\gamma=5/3$ is adopted. Effects of parallel electron drift, resistivity and thermal conductivity are included. The eigenvalue problem reduces to three ordinary differential equations which are presently under standard numerical investigation.

*Work performed under the auspices of the USDOE.

2D12

Reconnection Problem on Two Time Scales

Pung Nien Hu

Courant Institute of Mathematical Sciences
New York University

ABSTRACT

Reconnection of magnetic fields in a plasma is analytically studied by investigating the plasma and magnetic field responses of a two-dimensional tearing configuration when a periodic perturbation is applied to its boundary conditions. Assuming small driving frequency ($\sim\varepsilon$) and small resistivity ($\sim\varepsilon^2$), we found that there are actually two time scales in the tearing layer, one is the Alfven time scale and the other is the usual resistive time scale. A surface current is formed initially and the magnetic fields reconnect on the fast time scale as the current spreads. The seemingly unexpected fast time scale existing in the tearing layer is attributed to the small resistive effect in a thin region. The inner solutions of magnetic field and velocity are both matched with their outer solutions. Their evolution on the slow time scale can be determined by solving the equations for the next order.

This work was supported by U.S. DOE Contract No. DE-AC02-76ER03077.

Poster Session

DECAY INSTABILITY OF KINETIC ALFVEN WAVE IN AN INHOMOGENEOUS PLASMA

David W. Ross*, Abhijit Sen, and A. K. Sundaram
Physical Research Laboratory
Ahmedabad 380 009, India

Direct heating of ions by Alfven waves in low beta plasmas can occur only through nonlinear mechanisms. The theory of the decay instability of the kinetic Alfven wave into a second kinetic Alfven wave and an ion acoustic wave, which has been given for the case of plane waves[1], is here extended to the inhomogeneous plasma case. First, we apply standard WKB methods[2] to show that the criteria for absolute instability cannot be satisfied and to estimate the convective growth. Second, we begin a more rigorous study, deriving the appropriate nonlinearly coupled second order differential equations, and describing analytical[3], and numerical methods of solution. The problem is complicated by the fact that the nonlinear interaction can be strongest near the turning points of all three waves, so that even the pump wave must be described in terms of Airy functions.

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*Permanent Address: Fusion Research Center, The University of Texas at Austin. Work partially supported by the U.S. Department of Energy.

1. A. Hasegawa and L. Chen, Phys. Fluids 19, 1924 (1976).

2. M. N. Rosenbluth, Phys. Rev. Lett. 29, 565 (1972).

3. R. White et al., Nucl. Fusion 14, 45 (1974).

Poster Session

EFFECTS OF SAWTEETH ON IMPURITY TRANSPORT AND RADIATION LOSSES *

Fredrick H. Seguin
and
Richard Petrasso

American Science & Engineering, Inc.
Cambridge, Massachusetts 02139

Recent experimental results provide motivation for theoretical investigations of possible effects of sawteeth on various aspects of impurity transport in different types of tokamak discharges. Soft x-ray data have been used to follow the time evolution of the spatial distributions of impurities injected into the Alcator-C plasma. These data show that the magnetic field changes associated with internal disruptions momentarily allow greatly enhanced radial impurity transport within the plasma core: the radial density profile of each ionization state is abruptly flattened in the core each time a disruption occurs. The effect on impurity inflow can be large. During the inflow stage, the radial impurity profile is hollow, and profile flattening can result in the abrupt movement of a large quantity of material into the plasma center.

For purposes of modeling these diffusion processes, it is assumed that impurity transport in the absence of internal disruptions is governed by the simple diffusion equation with constant diffusion coefficient (previous work** indicates that this may be a reasonable assumption). The impurity density profile is allowed to evolve in time according to this equation, but periodically it is flattened in the central region, conserving particles.

For modeling injection experiments, the initial condition used is that the impurities be concentrated in a shell near the outer surface of the plasma. In the context of this model, internal disruptions can greatly reduce the impurity inflow time and modestly decrease the impurity confinement time (the size of these effects depends on the disruption frequency and on the q profile). Impurity particles therefore spend less time in the plasma, so each particle contributes less to radiative power losses. But it also turns out that more particles actually penetrate the core, leaving the time integral of the central impurity density unchanged. Therefore, in the context of injection experiments, the model predicts that sawteeth should cause significant changes in details of the transport process but no change in the total power lost through radiation. For steady state situations (inflowing impurities balancing escaping impurities), the model predicts that sawteeth cause no change in equilibrium levels.

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* This work has been supported by the U. S. Department of Energy.

** F. H. Seguin, R. Petrasso, M. Gerassimenko, E. Marmar, J. Rice, and J. Terry, Bull. Am. Phy. Soc. 26, 976 (1981).

2D15

Generation of Suprathermal Ions in Magnetic Traps*

B. Hafizi and R. E. Aamodt

Science Applications, Inc.
Plasma Research Institute
934 Pearl Street
Boulder, Colorado 80302

A theory of fast-ion generation in magnetic traps due to drift cyclotron loss cone (DCLC) modes is presented, providing a possible explanation for the structure of the perpendicular ion-energy distribution function and the temporal evolution of the DCLC mode. The implications of the theory with regard to the applicability of quasi-linear theory, as well as a detailed comparison with earlier work, are given.

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2D16

FIELD SWELLING INSTABILITY IN ANISOTROPIC PLASMAS*

B. Basu
Boston College, Newton, MA 02159

and B. Coppi
Massachusetts Institute of Technology, Cambridge, MA 02139

We consider collisionless plasmas imbedded in a magnetic field in which the electron temperature is anisotropic relative to the direction of the magnetic field and considerably higher than the ion temperature. A new instability[1] is found to be excited when the transverse temperature begins to exceed the longitudinal temperature and the plasma motion is allowed to be decoupled from that of the magnetic field lines. In this case the transverse electron thermal energy is transported toward the regions where the magnetic field is weakened by the perturbation by a particle flow and an effective finite thermal conductivity along the magnetic field lines. The relevant instability criterion is

$$1 < \frac{T_{e\perp}}{T_{e\parallel}} \frac{\beta_\perp}{1+\beta_\perp} < 2 \quad , \tag{1}$$

where $\beta_\perp = 8\pi n T_{e\perp}/B^2$, and is considerably less severe than the onset criterion for the well known mirror instability.[2] In fact the latter is derived under the assumptions that: a) the "frozen-in condition" ($\underline{E}+\underline{v}\times\underline{B}/c=0$) is valid and b) the effective thermal conductivity along the magnetic field is negligible. While criterion (1) refers to the slow magnetosonic wave becoming unstable, when

$$\frac{T_{e\perp}}{T_{e\parallel}} \frac{\beta_\perp}{1+\beta_\perp} > 2 \tag{2}$$

the fast magnetosonic wave becomes unstable. These modes can be relevant to the excitation of magnetic reconnection processes.

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*Sponsored in part by the A.F. Geophysics Laboratory (AFSC).

[1]B. Basu, and B. Coppi, M.I.T. Center for Space Research Report CSR-TR-81-4 (Cambridge, MA, 1981).

[2]W.B. Thompson, Reports on Progress in Physics (The Physical Society, London, 1961), Vol. 24, p.363 .

Exploration of Bifurcated, High-Beta Equilibria

D J Elkin and S Johnston

Plasma Physics Laboratory
Columbia University
New York, New York 10027

The cusp catastrophe surface is utilized to analytically model a rectangular boundary, ideal MHD tokamak equilibrium manifold having nonlinear profiles. The structure of bifurcations governed by β_p is revealed and a stability theory is formulated, derived from the finite dimensional part of the potential energy functional.[1] An identification of the ballooning mode second stable region is emerging.

At large aspect ratio the bifurcation set is a cusp. At finite aspect ratio a curious quadratic dependence of the eigenvalues upon the parameters determines a diamond pattern - a projection from the union of four cusp catastrophe surfaces - the interior of which denotes multiple equilibria. This is apparently the domain where it is possible for the ballooning mode to be unstable.

Restrictions upon and relationships among the dimensions, the parameters, and the equilibrium solutions for viability of the theory are presented in the large aspect ratio limit. Greater shear or stronger nonlinearities produce less divergent bifurcations. In finite aspect ratio a basis of Coulomb wave functions is derived and the succeeding calculation is sketched. The theory is adaptable to a circular cross-section, its qualitative features apply to a general boundary, and a three-dimensional version can be devised. Stellarator equilibria may be similarly treated.

The nonlinear stability of bifurcated equilibria to modes that cumulatively cause an axisymmetric perturbation of the flux surfaces follows immediately. Ballooning modes can provide a means of jumping from one equilibrium to another. The attainment of a stable equilibrium in the unstable region would help to explain why it has proved difficult to observe them in experiments. A path to the determination of ballooning mode stability promises to illuminate the following concern: What are the optimum conditions upon the dimensions and profiles for confinement according to ideal MHD? Better confinement may be achieved for a less stable plasma.

An experiment seeking bifurcated equilibria, distinguished by the location of the magnetic axis, is suggested.

1. D J Elkin and S Johnston, Sherwood Theory Meeting, 2C20 (1981).

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TRAPPING CURRENT IN THE THERMAL BARRIER REGION OF A TANDEM MIRROR MACHINE*

R. Carrera and J.D. Callen

Nuclear Engineering Department
University of Wisconsin
Madison, Wisconsin 53706

The distribution function in the trapped velocity space of the thermal barrier of a tandem mirror machine[1] is determined by the competition between charge exchange particle pumping and particle input via Coulomb scattering of the passing central cell ions. The problem of determining the steady state distribution function in the entire machine has been solved by considering the $O(\lambda)$ ($\lambda \sim \nu_{coll}/\omega_b$) linearized Fokker-Planck equation in the various mirror cells and within the square-well approximation. For a barrier mirror ratio $R \gg 1$ pitch-angle diffusion will dominate energy diffusion in the trapped region. In the limit $\eta \ll 1$ (η = ratio of number of particles in the barrier region to central cell) and $x_o^2 \gg 1$ ($x_o^2 = \phi_b/T$) the expression for the trapping current reduces to the form $j_t = (n_{bp}^2/aT^{3/2})\, R\kappa$ where n_{bp} = density of barrier passing particles, $a = (2/m)^{3/2}\,\Gamma^{-1}$, $\Gamma = (4\pi q^4/m^2)\ln\Lambda$, $\kappa = (2/x_o)[1 + (\lambda_{cx}^*/\lambda_{cx})^{1/2}]$, $\lambda_{cx}^* = x_o/2R$, $\lambda_{cx} = \tau_{cx}/\tau_s^b$, τ_{cx}^{-1} pumping rate, and τ_s^b = barrier scattering time. As the pumping rate is increased the distribution function contours wrap around the loss boundary in velocity space ($\Delta\zeta \sim \lambda_{cx}^{1/2}$, $\zeta = v_\parallel/v$) and the analysis based on the smallness of λ becomes invalid. Therefore for pumping rates greater than the effective trapping frequency (equivalent to $\Delta\zeta \sim \lambda_{cx}^{1/2} < \Delta\zeta^* \sim \lambda_{cx}^{*1/2}$ or filling ratio $g = n_b/n_{bp} < 2$) the trapping current is determined by a boundary layer analysis[2].

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*Work supported by the U.S. Department of Energy.

[1]D.E. Baldwin and B.G. Logan, Phys. Rev. Lett. 43, 1318 (1979).

[2]R. Carrera, J.D. Callen, and K.C. Shaing, Bull. Am. Phys. Soc. 26, 902 (1981) (to be published).

POSTER SESSION

THREE DIMENSIONAL "INCOMPRESSIBLE" PLASMA EVOLUTION

M. S. Chu
General Atomic Company
San Diego, California

ABSTRACT

Strauss' reduced equations[1] for a large aspect ratio tokamak have been generalized to an arbitrary high current configuration. The new reduced equations are obtained from the primitive equations by adopting a special gauge for the electric field. The fast compressional phenomenon is eliminated by assuming $\vec{\nabla}\cdot d\vec{v}/dt = 0$ and long parallel wavelength $\vec{B}\cdot\vec{\nabla} \sim \vec{J}\cdot\vec{\nabla} << \vec{\nabla}_{\perp}$. No other assumptions are made for the plasma pressure and velocity.

[1]Strauss, H. R., Phys. Fluids 19, 134, 1976.

*Work supported by Department of Energy Contract DE-AT03-76ET51011

Suppression of Magnetic Islands by RF Driven Currents*

Allan Reiman†
Physics Department, University of Maryland
College Park, MD 20742

and

Plasma Physics Laboratory, Princeton University
Princeton, N.J. 08544

The quasilinear theory for the saturation of nonlinear tearing modes[1] is modified to include rf driven currents. It is shown that the presence of lower hybrid driven currents can strongly suppress the growth of magnetic islands. Because we are primarily interested in driving rf currents in the outer region of the plasma, where the $q = 2$ surface lies, and where the equilibrium current density is relatively low, the efficiency of the rf current drive is less of an issue than it is for other applications. For a particular equilibrium whose nonlinear evolution was extensively studied by Waddell et al.[2] (and which describes PLT prior to a major disruption), the saturated island widths are sufficiently small that destabilization due to nonlinear coupling does not occur, and disruption is prevented.

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†Present Address: Plasma Physics Laboratory, Princeton University, Princeton, N.J. 08544

1. R. B. White, D. A. Monticello, M. N. Rosenbluth, and B. V. Waddell, Phys. Fluids 20, 300 (1977).
2. B. V. Waddell, B. Carreras, H. R. Hicks, and J. A. Holmes, Phys. Fluids 22, 896 (1979).

Poster Session

2D21

3-D MHD Studies of High-β Tokamak Discharges*

W. Park, R. Izzo, D. A. Monticello, and R. B. White
Plasma Physics Laboratory, Princeton University
Princeton, N.J. 08544

Three-dimensional MHD simulation studies of high-β tokamak discharges have been reported with results in agreement with experimental measurements.[1,2] These studies which utilized the high-β reduced tokamak equations[3] did not include the effects of the large thermal conductivity $K_{\parallel}$ parallel to the magnetic field.

In Ref. 1, we reported a study of the high-β plasma behavior during a time span short compared to the time necessary to reach saturation of the MHD modes. To study the long time behavior of high-β discharges, such as the saturation level and the sawtooth oscillation, the incorporation of the effect of $K_{\parallel}$ becomes necessary. This is due to the fact that without the thermal conductivity, a shock structure with a singular pressure gradient eventually develops, invalidating further computation.[4] Another reason is that the large $K_{\parallel}$ will effectively flatten the temperature profile inside magnetic islands and in the stochastic regions, thus playing an important role in the long time scale plasma behavior.

We have modified the 3-D MHD code HIB to include the effects of the large $K_{\parallel}$ and studied the long time scale behavior of the PDX high-β discharges. The temperature profiles remain flat inside magnetic islands and in the stochastic regions throughout the simulation. The effects of this phenomenon on the saturation level and the sawtooth oscillation are discussed. These results are also compared to the long time scale behavior of low-β plasma discharges.

*This work was supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

1. W. Park et al., Proc. of US-Japan Theory Workshop on 3-D Studies, Oak Ridge, TN, October (1981).
2. B. Carreras, Bull. Am. Phys. Soc. 26 (1981) 917
   J. Holmes et al., Proc. of US-Japan Theory Workshop on 3-D MHD Studies, Oak Ridge, TN, October (1981).
3. H. Strauss, Phys. Fluids 20 (1977) 1354.
4. D. A. Monticello, et al., IAEA, Brussels (1980) Vol. I, p 227.

Poster Session

MAGNETIC TURBULENCE, ERGODICITY AND ANOMALOUS THERMAL CONDUCTION IN TOKAMAKS

F.A. Haas and A.Thyagaraja.

Culham Laboratory, Abingdon, Oxon. U.K.
(Euratom/UKAEA Fusion Association)

We have previously investigated (1), (2) a two-fluid magnetic turbulence interpretation of anomalous electron thermal conduction in tokamaks. In the present paper the work is further developed and compared and contrasted with an alternative theory based on ergodic field line wandering (3). We consider the concepts of turbulence, ergodicity and rational surfaces, and discuss their usefulness in explaining experiment.

In our earlier work we studied a cylindrical model of tokamak and showed the effective radial electron thermal diffusivity, $\chi_{\perp e}$, to be

$$\chi_{\perp e} = \bar{\chi}_{\perp e} + \bar{\chi}_{\parallel e} \ \varepsilon^2 \Gamma_e,$$

where ε is the magnetic fluctuation level $\left(\frac{\delta B_r}{B_0}\right)$, $\bar{\chi}_{\perp e}$ is the neoclassical value of the radial thermal diffusivity, and Γ_e expresses the radial (r), modal and frequency dependence of the fluctuations. The second term, which represents an enhancement over $\bar{\chi}_{\perp e}$, is due to a phase-lag between thermal inertia and mean electron streaming on the one hand and parallel thermal conduction on the other. We show here that very low frequencies (ion inertia negligible ie. $\nu \ll 30$ kHz) are unimportant in this respect and hence tearing modes do not directly lead to enhancement. Frequencies of order 100 kHz appear to be significant, and for typical fluctuations lead to $K_{\perp e} \sim 10^{17}$ cm^{-1} sec^{-1}, which is in qualitative agreement with experiment.

Rechester and Rosenbluth (3) have put forward a turbulence theory based on the assumption that the tokamak magnetic field can be represented as the sum of a mean part and random static magnetic fluctuations. We observe that their "stochastic" thermal diffusivity, $\chi_{\perp st}$, is zero except at resonant points. Since the latter are of measure zero we conclude that $\chi_{\perp st}$ cannot account for the anomaly.

We have previously remarked (2) that although ergodicity may occur in time-dependent situations, it is not required by our interpretation. We investigate the possibility that in a static system a magnetic field line can fill a finite region ergodically. Such a region appears to be incompatible with the equilibrium constraints. This suggests that non-linearly saturated steady-states predicted by tearing mode calculations cannot show ergodicity.

(1) Thyagaraja. A., Haas, F.A., and Cook. I., (1980) Nucl. Fusion 20, 611.
(2) Haas. F.A., Thyagaraja. A., and Cook. I., (1981) Plasma Physics 23, 1027.
(3) Rechester. A.B., and Rosenbluth. M.N., (1978) Phys. Rev. Lett. 40, 38.

NUMBER OF SPATIAL FOURIER MODES CONTROLLING NAVIER-STOKES FLOWS*

Yvain M. Treve**, La Jolla Institute

Pursuing our search for the number of modes which are necessary and sufficient to generate qualitatively correct approximations to the solutions of MHD problems we have obtained the following results:

1) In collaboration with C. Foias, O. P. Manley, and R. Temam[1] we have derived a rigorous estimate of the number of modes which are sufficient to determine the solution of the hydrodynamic Bénard problem. In the case of turbulence a physical interpretation of this sufficient number shows that it may not be much greater than the necessary and sufficient number. This result may be generalized to the MHD version of the problem.

2) The Bénard problem possesses a symmetry which is broken above a certain Rayleigh number thereby causing a discontinuity in the convected heat transport. Numerical experiments will be discussed.

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** Mailing address: 125 San Rafael Ave., Santa Barbara, CA 93109.

1. C. Foias, O. P. Manley, R. Temam, and Y. M. Treve. Asymptotic numerical analysis of the Navier-Stokes equations, in preparation.

2D24

AMBIPOLAR DIFFUSION IN QUASILINEAR THEORY

H.L. Berk and K. Molvig*
Institute for Fusion Studies
University of Texas
Austin, Texas 78712

It is well known that in equilibria with an ignorable coordinate, particle diffusion due to collisions leads to an intrinsic ambipolar flow to lowest order in the Larmor radius. It is only in higher order, that an intrinsic nonambipolar diffusion develops, from which one can determine the ambipolar field by solving for the electric fields that equate the flow rates. We have examined a similar problem using quasi-linear formalism where diffusion is due to wave turbulence. Previous analysis have assumed that eigenfunctions are localized to each field line, with the result that ambipolar flow is intrinsic. We have applied WKB theory to give the eigenfunctions a spatial structure. By ordering the slowness of the spatial variation of the eigenfunction to the same order of the smallness of the gyroradius, a theory develops where there is nonintrinsic charge diffusion if the turbulent waves are convective in space. The time varying ambipolar potential is determined by the condition that quasineutraility be maintained.

*Massachusetts Institute of Technology, Cambridge, Mass.

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Gyrokinetic Particle Simulation of Drift Wave Turbulence*

W. W. Lee, L. Chen, C. Z. Cheng, and W. M. Tang
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

Particle simulation using a newly developed 2-and-1/2 dimensional gyrokinetic code has been carried out to study steady-state drift wave turbulence in slab geometry. The code is based on the gyrokinetic formulation of the Vlasov-Poisson system[1], which retains the gyroradius effects but not the gyromotion. Furthermore, in order to maintain the zeroth-order density profile in the simulation, a multiple spatial scale scheme[2] has been incorporated into the code, in which the equilibrium scale lengths are separated from those of the perturbed quantities. The simulation system has no shear, and is periodic in both x and y directions for the waves as well as for the particles. The density gradient is in the x direction and the magnetic field is in the y - z plane with $B_z \gg B_y$.

The simulation results have indicated that the development of the drift wave turbulence has two distinct stages. In the growth stage, the inverse cascade process is dominant where the energy of the linearly unstable modes has been observed to flow in the direction of diminishing k_y. Consequently, $k_y = 0$ modes are greatly enhanced. The frequency spectra at this stage are sharply peaked. The second stage is characterized by the dual cascade processes where the energy is sloshing back and forth between different k_y modes. In this saturated state, the frequency spectra become considerably widened and the energy spectra is broadly peaked around $k_y = 0$. In the mean time, a dramatic increase in particle diffusion has also been observed. Details will be reported.

*This work supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

1. W. W. Lee, Princeton Plasma Physics Laboratory Report 1838 (1981).
2. W. W. Lee and L. Chen (in preparation).

Poster Session

Diffusion In ZT-40M Using A 1-D Radial Transport Code.* R. B. HOWELL, Los Alamos National Laboratory.--The diffusion equations for the electrons and the impurity ions have been solved for the ZT-40M plasma. The equations for the impurity ions include ionization and recombination. The diffusion coefficient for the electrons was found by matching the experimentally measured diffusion of the electron density profile to the calculated diffusion.

The numerical scheme uses 10-mesh points and uses the Crank Nicholson implicit method where the differences are centered in both space and time. At the outer boundary the density is set to zero. In addition a loss term is added to the diffusion equation at the last mesh point for both the electrons and the impurity ions. The initial condition for the electrons uses a cubic spline fit to the measured electron density profile. The initial condition for the impurity ions has the neutral state containing all the impurity particles and uniform across the radius.

The results indicate a diffusion coefficient for the electrons which is 1.5×10^5 cm^2/sec from 0.4 ms to 0.6 ms for the 200 kA condition. The global particle confinement time starts at about 0.25 ms and increases to 1.0 ms by 0.4 ms into the discharge. The comparison between measured impurity emission and calculated emission profiles is still in the early stages.

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*Work performed under the auspices of US DOE.

BGK Solutions to The Free Electron Laser Instability

Barton Lane and Ronald C. Davidson

The saturated final state for the free electron laser instability is analyzed. It is assumed that a relativistic electron beam propagates in the z-direction through an applied transverse, helical wiggler field

$$\underset{\sim}{B}_o(\underset{\sim}{x}) = -\hat{B}_w(\cos k_o z\, \hat{\underset{\sim}{e}}_x - \sin k_o z\, \hat{\underset{\sim}{e}}_y)$$

where B_w is a constant and $\lambda_o = 2\pi/k_o$ is the wiggler periodicity. The final state is restricted to consist of a single circularly polarized electromagnetic wave with vector potential

$$\delta\underset{\sim}{A}(\underset{\sim}{x},t) = \frac{\delta\hat{B}_t}{k}[\cos(kz - wt)\hat{\underset{\sim}{e}}_x + \sin(kz - wt)\hat{\underset{\sim}{e}}_y]$$

and a transversely "cold" distribution function $f_b = n_b\delta(P_x)\delta(P_y)F(z,p_z,t)$, where $\underset{\sim}{P}_\perp = \underset{\sim}{p}_\perp - (e/c)\underset{\sim}{A}_\perp$ is the conserved, transverse canonical momentum. It is shown that functions $F(z,p_z,t)$ can be found which satisfy the exact Vlasov-Maxwell equations by a method analogous to the electrostatic BGK procedure. The constraint that the final state have the same average particle, momentum and energy densities as the initial state is then applied to restrict the possible final states. A discussion and numerical analysis of the nature of the BGK distribution functions and the restrictions on the saturated wave amplitude due to the conservation constraints will be presented.

PARAMETRIC INSTABILITIES DURING ELECTRON-CYCLOTRON RESONANCE HEATING OF TANDEM MIRRORS

D. R. Nicholson
Department of Physics and Astronomy
The University of Iowa
Iowa City, Iowa 52242

Recent experimental observations[1,2] during electron-cyclotron resonant heating[3-5] of the Phaedrus tandem mirror are not in accord with the standard theory. The possibility that these results are due to a parametric instability involving the heating wave and two high frequency decay products is explored. The high frequency decay products considered here (in contrast to the mixture of high and low frequency decay products considered in Ref. 6) are magnetized Langmuir waves and electron-cyclotron waves. If growth rates of the same order as in the unmagnetized laser-fusion case[7] are found here, these instabilities will have a significant effect on the heating experiments.

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[1] J. Kesner, R. S. Post, and D. Smatlak, private communication.

[2] D. Smatlak, Ph.D. thesis, University of Wisconsin, 1982.

[3] L. Friedland and M. Porkolab, Phys. Fluids <u>24</u>, 1097 (1981).

[4] M. Porkolab, UCRL-52634 (1978).

[5] M. Porkolab, L. Friedland, and I. Bernstein, UCRL-84235 (1980).

[6] E. Ott, B. Hui, and K. Chu, Phys. Fluids <u>23</u>, 1031 (1980).

[7] C.-S. Liu and M. Rosenbluth, Phys. Fluids <u>19</u>, 967 (1976).

<u>Special Request</u>: Due to teaching obligations, it is requested that this poster appear on the morning or afternoon of Tuesday, April 27.

Anisotropy Driven Compressional Alfvén Effects*
in a Hot Electron Plasma

X. S. Lee, K. T. Tsang, and P. J. Catto

Science Applications, Inc.
Plasma Research Institute
934 Pearl Street
Boulder, Colorado 80302

The hot electron population in an electron cyclotron heated plasma is strongly anisotropic in its velocity space distribution. This anisotropy is a source of free energy that may excite instabilities. For frequencies below the ion cyclotron frequency, Ω_i, a ballooning-interchange/compressional Alfvén eigenmode equation is derived using the gyrokinetic technique and assuming a bi-Maxwellian distribution function with $T_{||} \neq T_\perp$ for the hot electron population. The background plasma is assumed to be isotropic and Maxwellian. This eigenmode equation is similar to that derived previously for an isotropic hot electron species.[1] The notable difference is that the compressional Alfvén mode can also be destabilized by anisotropy when $T_\perp/T_{||} > 1$ in the limit $|\omega| << |\omega_{*h}|, |\omega_{dh}|$ (where ω_{*h} and ω_{dh} are the diamagnetic and magnetic drift frequencies of the hot electrons). The finite hot electron gyroradius correction, however, is found to be stabilizing for both curvature and anisotropy destabilized plasmas.

Effects of the coupling of interchange and compressional Alfvén, as well as the finite frequency shift in the hot electron compressibility term are investigated.

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*Work supported by the U. S. Department of Energy under Contract No. DE-AC03-76-ET-53057 with Science Applications, Inc.

[1] K. T. Tsang and P. J. Catto, SAI Report No. SAI-254-81-386-LJ/PRI-34, to be published in Phys. Fluids.

2D30

1982 Sherwood Meeting
Sante Fe, New Mexico
April 25-28, 1982

CURRENT DRIVE BY LH WAVES IN THE PRESENCE OF A DC ELECTRIC FIELD*

V. Krapchev
Massachusetts Institute of Technology
Plasma Fusion Center
Cambridge, Massachusetts 02139

The DC electric field in a tokamak leads to significant changes in the distribution function from the Maxwellian one at velocities near the Dreicer critical velocity (V_c). In recent LH current drive experiments it is found that steady state RF current is produced only at low densities [1]. In this case the spectrum of the waves in velocity space is close to V_c. The discrepancy between the present theory [2] and experiments calls for a reexamination of the theory and the effect of a DC electric field should be taken into account.

We study the two dimensional Fokker-Planck equation in which both RF diffusion and DC electric field are included. An approximate analytic solution for the distribution function at $V < V_c$ will be presented when the wave spectrum is located at velocities smaller than V_c.

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POSTER SESSION

KINETIC BALLOONING MODES IN TOKAMAKS*

R. R. Dominguez, R. W. Moore, and C. S. Liu
General Atomic Company
San Diego, California

ABSTRACT

In recent neutral-beam heated tokamak experiments[1] it has been observed that energy confinement is generally degraded with increasing beam power. Clearly, an understanding of the basic mechanisms underlying this unfavorable scaling is an important issue in tokamak theory. In the present work, we suggest the possibility that a beam excited instability is the fundamental mechanism at work. We develop a linear kinetic theory of the ballooning mode in toroidal geometry, including temperature anisotropy of the beam, diamagnetic drifts and precessional drifts of both the hot ions and background plasma. Employing beta (β) of the beam and background plasma as a small parameter, the coupled Maxwell equations are reduced to a single eigenmode equation. Solutions for the eigenvalues exhibit a resonant hot ion instability, localized in the region of "bad" curvature. Detailed parametric dependences of the instability will be discussed while the non-linear saturation will be considered elsewhere.[2]

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*Work supported by Department of Energy Contract DE-AT03-76ET51011

Stability of Ballooning Modes In The Elmo Bumpy Torus (EBT)* 2D32

K. Nguyen and T. Kammash
University of Michigan
Ann Arbor, Mich. 48109

Using a quasi-kinetic approach in a slab model we investigate the stability of low frequency electromagnetic modes in an EBT-type geometry in which axial as well as transverse magentic field gradients are taken into account. With the hot electron component treated as highly anisotropic and situated in an isotropic background plasma that is located in a mirror geometry, with mirror ratio M and length L, a differential equation of the Mathieu type is obtained for the perturbed potential. When variations along the magnetic field are ignored the equation in question reduces to the standard form of VanDam and Lee(1) used in the study of the interchange modes in EBT. Assuming the same density gradient for all species, the Mathieu equation is analyzed for the stability of modes propagating perpendicular to the magnetic field. We obtain a limit on the core beta which displays a dependence on the hot electron beta similar to that of Nelson and Hedrick(2). An approximate upper bound on the core beta is obtained which by analogy to the pure interchange case (with axial variations ignored) should also be enhanced when the hot electrons are made relativistic(3).

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*Work supported by DOE

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D-D TOKAMAK REACTOR ASSESSMENT*

D. C. BAXTER, R. N. BYRNE, A. E. DABIRI, D. R. DOBROTT, J. E. GLANCY,
W. K. HAGAN, J. B. MCBRIDE, S. TAMOR
Science Applications, Inc., La Jolla, California, USA

This paper describes results of D-D tokamak studies whose goal is to evaluate the potential of deuterium fuel for practical fusion generation in tokamaks. Previous DT tokamak reactor designs such as STARFIRE[1] are used as a point of reference in assessing the advantages/disadvantages of D-D tokamaks relative to DT. Our studies emphasize careful treatment of the physics processes that are particularly important for modelling the high temperature regime of D-D reactor operation. For example, our treatment of the reaction kinetics of the D-D reaction chain contains detailed consideration of such effects as nuclear elastic scattering (NES) of the fusion products, which is a potentially important mechanism for enhancing energy transfer to the plasma ions at the high temperatures of advanced fuel reactor operation. We have also developed a fast subroutine for calculating energy transfer by synchrotron radiation that is well suited to incorporation in our D-D reactor simulator code DDMAK. This model is capable of predicting not only total energy loss but profile effects as well, and thus is an improvement over the global radiation models used heretofore.

In performing our D-D reactor assessments, we employ two D-D reactor modelling codes. The first of these codes, DDMAK, was developed by us for this purpose and is a one dimensional, time dependent D-D tokamak reactor simulator code. The code calculates the radial profiles and the time evolution of the electron density and temperature, the ion densities for p, D, T, He^3 and He^4, a common ion temperature and up to two impurity species. Power loss fractions in neutrons, diffusing plasma particles and heat, synchrotron and bremsstrahlung radiation are determined which provide the basis for technology assessments of many of the reactor subsystems. The second code used in our studies is the TRAC-II code[2], developed at Argonne National Laboratory. This is a fast global code in which the plasma profiles are specified, i.e., no attempt is made to calculate evolution of the spatial profiles in response to plasma and radiation transport. Thus, DDMAK is used for detailed spatial modelling of the reactor plasma dynamics. Profile information from DDMAK is then used as input to TRAC-II, which is a valuable tool for performing reactor parameter surveys and sensitivity studies.

We describe the results of our reactor modelling studies and present preliminary results of a cost analysis for DD tokamak reactors. We also compare possible D-D reactor designs that have emerged from our assessment to existing D-T reactor designs.

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FORMATION, EQUILIBRIUM AND STABILITY CONSIDERATIONS FOR ACCELERATED COMPACT TOROIDS

J. H. Hammer and C. W. Hartman
Lawrence Livermore National Laboratory
Livermore, California 94550

Acceleration of compact torus (CT) plasma rings for purposes of current drive in tokamaks, inertial confinement fusion and other applications has recently been suggested.[1] We present here the results of simple MHD models applied to the formation, equilibrium and stability of accelerated CT's produced by a coaxial plasma gun. Concerning formation, we find that a modest expansion of the gap between the inner and outer conductors of the plasma gun at some position along the gun axis is necessary to form an isolated ring. Given an isolated CT undergoing uniform acceleration (equivalent to a CT in an axial gravitational field in the accelerated reference frame), we find from the equilibrium equations that the matter on each flux surface has a tendency to pile up at the "lowest" point. The piling up causes the local plasma β to approach K, the ratio of accelerating force to equilibrium magnetic force, independent of the pre-acceleration $\beta = \beta_0$, if $\beta_0 < K$. Stability to pressure gradient/curvature driven modes may then put an upper limit on the allowable K of an accelerator. Another stability consideration for plasma gun accelerated CT's is the slip mode-slippage of the accelerating toroidal flux around the plasma ring. We find stability to slipping as long as $K \lesssim 1$. The infamous tilting instability is suppressed in these configurations by the large center conductor.

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Poster Session

2D35

MAGNETIC PERTURBATIONS IN TOKAMAKS

R. N. Morris and Glenn Bateman
School of Nuclear Engineering and Health Physics
Georgia Institute of Technology
Atlanta, Georgia 30332

When the vacuum magnetic field from a localized coil arrangement (e.g., from a bundle divertor) is superimposed on an axisymmetric plasma equilibrium, it is found that there is a threshhold beyond which the perturbation produces complete lack of field line confinement outside of a given minor radius. Within the context of this model, we have found that the best available hybrid bundle divertor design[1] at full current produces a lack of field line confinement over most of the plasma. Alternative hybrid bundle divertor designs are being considered in which the divertor coils are tilted or shortened to minimize the problem.

In a separate line of research, the effect of an applied 7/4 magnetic island on the amplitude of a 2/1 saturated tearing mode was studied with a computer code which can self-consistently determine the amplitudes of several helical harmonics simultaneously in a circular cylinder.[2] Starting with typical experimentally measured profiles,[2] it was found that the 7/4 islands are swallowed up by the 2/1 islands and have no effect if the 2/1 tearing mode is already at full amplitude before the 7/4 mode is turned on. However, if the 7/4 mode is applied before the 2/1 has had a chance to grow, the local profile flattening at the 7/4 mode rational surface can significantly suppress the saturated amplitude of the 2/1 mode. Unfortunately, the combined widths of the 7/4 and 2/1 islands remain nearly constant over a wide range, and nearly equal to the width of the original 2/1 saturated tearing mode. The combined widths, including the sawtooth region, are also nearly constant.

This research is supported by the U. S. Department of Energy.

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Nonlinear Damping of Ion Cyclotron Waves and Harmonic Generation*

C. F. F. Karney† and A. Fukuyama
Okayama University, Okayama 700, Japan

We consider the interaction of a few waves at multiples of the ion cyclotron frequency with a collection of ions. For simplicity we take the waves to be electrostatic with $k_{\parallel} = 0$ and $k_{\perp}\rho_i \ll 1$. With only one wave present the particles are accelerated to higher perpendicular velocities where they interact more strongly with the wave leading to an enhanced damping.[1] Eventually the wave is extinguished. At this point the distribution of particles is bunched in Larmor angle. This non-Maxwellian distribution is unstable and the wave is exactly regenerated. This repeats giving rise to a periodic (in general, non-sinusoidal) variation in the amplitude of the wave. However, waves at other frequencies may also be generated by the non-Maxwellian distribution. For example, a wave at $n\Omega_i$ will give a distribution which excites a wave at $2n\Omega_i$. This stops the original wave from being exactly regenerated and the wave amplitudes have a much more complicated non-periodic behavior.

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†Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08544

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Poster Session

2D37

A Multi-Dimensional, Selfconsistent, Kinetic Numerical Transport Method For Treating Chemistry Dominated Edge Plasmas*

D. Morrison, R. Morse and G. Sowers
University of Arizona, Tucson

The structure of scrape off layer plasmas near divertor or neutralizer plates is strongly influenced by plasma chemistry which involves species streaming both to and from the plate, which leads to highly non-equilibrium velocity distributions. In some cases of interest the structure is also strongly influenced by large density and temperature gradients perpendicular to the confining $\bar{B}$ field. For the purpose of treating this latter class of problems a multi-dimensional, kinetic, numerical transport method has been developed which treats multi-species plasma chemistry and the electrostatic potential selfconsistently. The method employs as a grid in phase space the collisionless trajectories of the various species in the magnetic and electrostatic fields of the problem. Results of test problems will be shown.

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ANISOTROPY EFFECTS ON MICROWAVE ABSORPTION BY RELATIVISTIC ELECTRON RINGS IN EBT DEVICES*

D. B. Batchelor and R. C. Goldfinger†
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

S. Tamor
Science Applications, Inc.
La Jolla, California

A number of previous studies of microwave absorption by hot electron rings have been carried out using ray tracing methods in finite beta equilibria generated by a 2-D tensor pressure MHD equilibrium code.[1,2] A restriction on the studies has been that the absorption is calculated assuming an isotropic relativistic Maxwellian for the hot electron distribution function,

$$f(\underset{\sim}{p}) = n_A A e^{-\frac{mc^2}{T}\gamma}$$

where A is a normalization factor and $\gamma = (1 + p^2/m^2c^2)^{1/2}$. Recently, an absorption model has been developed which admits a much wider class of distribution functions of the form[3]

$$f(p) = \Sigma A_{ijk}(p^2)^i(\sin^2\theta)^j e^{-\frac{mc^2}{T_k}\gamma}$$

where $\sin\theta = p_\perp/p$. In this paper, we present preliminary results from the ray tracing code using the anisotropic model. Comparison is made with previous results using the isotropic model.

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†UCCND Computer Sciences, Oak Ridge, Tennessee.
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INTERMEDIATE MODE NUMBER BALLOONING STABILITY OF STELLARATOR-TOKAMAK HYBRIDS*

W. A. Cooper and B. A. Carreras

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

The intermediate mode number $n(1 << n << M$ = number of field periods) ballooning stability of stellarator-tokamak hybrid equilibria is investigated. We generate these equilibria from a 2-D Grad-Shafranov equation obtained from a set of reduced MHD equations that have been spatially averaged over a field period $2\pi R_o/M$.[1] The total safety factor (q) profile, the externally applied transform at the magnetic axis, and the externally applied transform at the edge of the plasma that result from the helical windings are prescribed independently one from the other. A ballooning mode equation obtained from linearizing the reduced set of MHD equations contains an averaged helical curvature term arising from the external windings in addition to the usual tokamak terms. We find that we can increase the critical beta (β_c) with the externally applied transform because the averaged helical curvature provides a stabilizing contribution. Of the two elements of the helical curvature, we have identified that the vertical component has a somewhat stronger stabilizing influence compared with the horizontal component.

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2D40

STRUCTURE OF WALL PLASMAS NEAR DIVERTOR NEUTRALIZER PLATES OR LIMITERS

by

Paul Gierszewski
MIT
P. McKenty, J. McCullen, and R. Morse
University of Arizona, Tucson

The structure of wall plasmas near neutralizer plates or limiters is calculated with a kinetic transport model which includes binary collision processes between the various ion, atomic, and molecular species, and the self consistent electrostatic field. A family of solutions is found which may be used in calculating removal of heat and impurities.

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Ion Loss-Cone Instabilities in Realistic 3-D Geometries

M. J. Gerver
Plasma Fusion Center, MIT, Cambridge, MA 02139

A code has been written which first solves the axial eigenmode equation (an ordinary second-order differential equation) for the DCLC and ALC modes along a given field line, for a given $k_\perp$, in a mirror cell; and then calculates the perpendicular group velocity and rate of spreading of a wave packet localized on that field line at that $k_\perp$, as well as the modification in growth rate and frequency due to the finite size of the wave packet. If WKB (perpendicular to the field lines) is even marginally valid for these modes, then this code should give us information about the 3-D eigenmodes for the ALC and DCLC instabilities, and tell us to what extent the stability criteria are modified by radial convection and other effects of finite radial geometry.

The code allows us to include fanning due to a quadrupole field, which would tend to make the orbits of wave packets ergodic. It also includes a self-consistent calculation of the equilibrium density of warm plasma trapped on one side of the potential peak. The finite ion cyclotron resonance width (due to the finite parallel ion temperature and to the axial variation in field) is taken into account; finite resonance width allows modes which are resonant at one place (where there is little warm plasma) to be stabilized by warm plasma at another place, where the field strength is slightly different. The fact that the code includes the evolution of the width and shape of the wave packet (as well as its position) means that the results are valid even when the group velocity has a large imaginary part (as it usually does).

Using a Fokker-Planck-like equilibrium for the TARA ion anchor with belly-band, we have found that local instabilities exist along certain field-lines, and for certain directions of $k_\perp$, even if there is a large amount of trapped warm plasma. These instabilities are axially localized in the outer part of the mirror cell, away from the warm plasma. Because this axial localization can occur more easily for higher frequencies, the local instabilities only occur for $\omega \gtrsim 4\omega_{ci0}$, and have local growth rates only a few tenths of ω_{ci0}. We will present results on the effects of radial convection and wave-packet spreading; preliminary results show that these effects cause large changes in the local growth rates, so that WKB is only marginally valid. Any calculation of warm plasma requirements for DCLC and ALC stability will have to include finite radial geometry effects, if it is expected to give results that have errors of less than ~ 50 - 100%.

2D42

Overstable Resistive Instabilities in the Diffuse Linear Pinch*

C. Ryu and R. C. Grimm
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

In the boundary layer treatment of resistive instabilities the dispersion relation which is obtained by asymptotically matching outer ideal MHD solutions to inner resistive MHD solutions gives, in general, complex frequencies for the normal modes of the system. For a simple slab model it was shown[1] that no overstable modes can exist. With toroidal geometry, analysis[2] of the inner solutions on a rational surface demonstrated the possibility of overstable modes at finite pressure and gave rise to the Δ_c criterion. In cylindrical geometry such overstable modes can exist if the pressure profile increases from the magnetic axis so that the quantity D_R is sufficiently negative. Using the matrix shooting method[3] we have studied the behavior of unstable modes in Tokamak and RFP like cylindrical configurations as D_R is made progressively more stabilizing. From the pure tearing configuration at zero pressure, the most unstable resistive mode has its growth rate reduced until it coallesces with a second resistive mode whose growth rate increases with pressure gradient. Further increase of the pressure gradient results in overstable modes which become damped for p' greater than some critical value (or alternatively for some $\Delta < \Delta_c$). We compare these full numerical solutions with the boundary layer treatment and discuss the implications to the resistive PEST program.

*This work supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

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Poster Session

2D43

A HYBRID LANGUAGE FOR LARGE CODES

by Oscar Buneman, Stanford University

As an alternative to learning CFT compiler psychology, one can achieve optimal CRAY coding by writing in a vernacular which is as transparent as Fortran (or other high-level languages) while retaining the power and control of Assembler (CAL). The obscurity and apparent clumsiness of straight low-level code can thus be avoided. The clue lies in making up "macros" and "opdefs" of one's own choice. The use of such a hybrid language has helped a great deal toward the completion of Stanford's three-dimensional ($2*128^3$ grid points), five million particle code. Sample sections of the code, and results of testing for correct plasma dispersion, will be presented at the meeting.

2D44

A THEORY OF MACROSCOPIC INVARIANTS*

Laurence S. Hall
Lawrence Livermore National Laboratory, University of California
Livermore, California 94550

The classical problem of determining the integrability of a Hamiltonian system is addressed and solved in two (configurational) dimensions. Conditions are found which admit to general integrability of the orbits for conservative systems; magnetic or coriolis forces are permitted within the theory together with the usual forces derivable from a scalar potential. When a system admits a given invariant, the invariant is found. A number of examples, including known and previously unknown invariants, are given. The theory also extends to the derivation of approximate invariants and a variational principle for the derivation of "best" approximations is formulated. Application is made to the problem of the general cubic potential with one symmetric coordinate: $V = (1/2)\,Ax^2 + (1/2)\,By^2 + Cx^2y + (1/3)\,Dy^3$. Although not yet worked through, the theory is applicable as well to more than two dimensions.

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Nonlinear Evolution of the Resistive Interchange Mode in the Cylindrical Spheromak*

J. DeLucia and S. C. Jardin
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

A study is made of the nonlinear time developement of the resistive interchange mode in the cylindrical spheromak. We look at effects on the mode growth due to nonlinear modification of the equilibrium profiles. The plasma is assumed to be incompressible and only modes of a given helicity are allowed to develop. The time advancement equations for the plasma quantities are

$$\frac{\partial}{\partial t} \chi + \bar{v}\cdot\nabla\chi = \eta(\Delta^{*}\chi - Mg) + c(t) ,$$

$$\frac{\partial}{\partial t} \frac{1}{\alpha^2} (g-M\chi) + \bar{v}\cdot\nabla \frac{1}{\alpha^2} g = \bar{B}\cdot\nabla \frac{\omega}{\alpha^2} + \eta\Delta^{*}g ,$$

$$\rho_o\left[\frac{\partial}{\partial t} \frac{\Delta^{*}A}{\alpha^2} + \bar{v}\cdot\nabla \frac{(\Delta^{*}A-M\omega)}{\alpha^2}\right] = \frac{k^2}{\alpha^4} \frac{\partial}{\partial\tau} (g^2-\omega^2) + \bar{B}\cdot\nabla \frac{(\Delta^{*}\chi-Mg)}{\alpha^2} ,$$

and

$$\rho_o\left(\frac{\partial}{\partial t} \omega + \bar{v}\cdot\nabla\omega\right) = \bar{B}\cdot\nabla g \quad .$$

Here $\tau \equiv m\theta + kz$ is the helical coordinate, $\alpha^2 \equiv m^2 + k^2r^2$, $M \equiv 2mk/\alpha^2$, $\Delta^* \equiv \alpha^2\nabla\cdot(1/\alpha^2 \nabla)$ and r, θ, z are the usual cylindrical coordinates. η is the plasma resistivity and ρ_o is the average fluid density. The magnetic field is given by $\bar{B} = (\hat{e}/\alpha) \times \nabla\chi + (\hat{e}/\alpha)g$ and the fluid velocity is given by $\bar{v} = (\hat{e}/\alpha) \times \nabla A + (\hat{e}/\alpha)\omega$ where χ, g, A, and ω are functions of r, τ and time and $\hat{e}$ is a unit vector in the symmetry direction.

The plasma variables and time advancement equations are fourier analyzed in τ. Finite differences are used in the radial coordinate with grid points packed about the singular surface. In order to avoid small time step restrictions we use a time advancement scheme which treats shear Alfvén wave terms and the resistive terms implicitly. This results in a block tridiagnal system of equation to be solved each time step for each fourier harmonic.

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PREDICTIVE POWER OF PERTURBATION THEORY IN CALCULATING THE EFFECT OF LOCALIZED RF FIELDS NEAR THE GYROFREQUENCY*

B. M. Lamb, G. J. Morales, and G. Dimonte
Department of Physics
University of California, Los Angeles, CA 90024

The energy change experienced by an ensemble of particles entering a spatially localized RF electric field of frequency ω near their gyrofrequency Ω is calculated using second order perturbation theory. The change in the parallel energy component yields the familiar expression for the ponderomotive effect when the adiabatic limit $(\omega - \Omega)\ \tau >> 1$ is taken, where τ is transit time through the field structure. In the non-adiabatic limit both perpendicular heating and a parallel energy change occur. The results of second order perturbation theory have been compared with numerical solutions of the exact equations of motion. As expected, excellent agreement is found when the electric field amplitude is small and produces minor perturbations in the trajectories. Unexpectedly good agreement is found between perturbation theory and numerical calculations when large electric fields are used. Numerically generated phase space plots have been produced for RF field frequencies both above and below the gyrofrequency. Complicated features in phase space plots appear when $\omega \lesssim \Omega$.

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A One-Dimensional Code for Field-Reversed Mirror Dynamics

R. A. Stark and G. H. Miley
Fusion Studies Laboratory
University of Illinois
214 Nuclear Engineering Laboratory
103 S. Goodwin Avenue
Urbana, Illinois 61801

A one-dimensional hybrid code has been developed to model the start-up of the Field-Reversed Mirror via neutral beam injection. The code combines a fluid model for electrons and low energy ions with a numerical multi-group kinetic model for ions from the beam. These two models have been developed separately, and are described in references 1 and 2; they have now been merged in the present code FROST (Field Reversal One-dimensional STart-up code).

As an example of the operation of FROST, we have simulated tangental injection in 2XIIB. A 15 amp/cm neutral beam was aimed 4 cm off-axis into a plasma stream of density $10^{13}/cm^3$, temperature 0.1 keV and radius 6 cm. The vacuum magnetic field was 4.65 kG and the wall radius was 12 cm. After 1.5 msec, the average ion density was $7x10^{13}/cm^3$, while the center line magnetic field was depressed by 22%. The circulating ion current at this time (700 A/cm) is about 19% of that required for reversal. The results of longer operation of the code will be presented for direct comparison with several reversal experiments in 2XIIB, where peak values were reached after 4 msec of injection.

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ENERGY REDISTRIBUTION IN IGNITING PLASMAS

L. Sugiyama and R. Englade
Massachusetts Institute of Technology, Cambridge, MA 02139

The thermal energy balance in igniting D-T toroidal plasmas is studied using a 1-D transport code that incorporates a model of the sawtooth disruption that we have found to reproduce existing experimental observations.[1] The energy deposition due to collisional slowing down of fusion α-particles concentrates near the center of the plasma and may lead to a thermal instability there. Due to the slower growth of the $m^{\circ}=1$ reconnecting mode in collisionless plasmas[2], the rapid sawtooth oscillations characteristic of sub-igniting plasmas do not occur and cannot be used to redistribute the excess central energy to the outer parts of the plasma. However, enhanced anomalous electron thermal conductivity[3] and effects due to the possible existence of $m^{\circ}=1$ magnetic islands produced by the reconnecting modes may prevent thermal runaway up to considerably higher temperatures.

This work was supported by the U.S. Department of Energy.

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A COMPUTATIONAL MODEL FOR LOWER HYBRID HEATING AND CURRENT DRIVE IN TOKAMAKS*

R. Englade and P.T. Bonoli
Massachusetts Institute of Technology
Cambridge, Mass. 02139

Realistic numerical simulations are an important adjunct of lower hybrid experiments in toroidal devices. They are useful in unfolding the complicated dynamical processes involved and in determining the relative importance of various physical effects. We report here on the continued development of a computer model for heating and current generation which incorporates a 1-D transport code and a ray tracing code.[1]

The basic ray tracing code takes into account the major radius dependence of the toroidal magnetic field and assumes no plasma in the region beyond the limiter radius. Other versions include the effects of more realistic models for the edge region and the toroidal equilibrium. The transport code assumes enhanced neoclassical ion conductivity and an electron thermal diffusion coefficient of the Coppi-Mazzucato type that has been modified to apply to situations in which non-ohmic auxiliary heating is important.[2]

Radially dependent bulk plasma quantities and the electron distribution function are obtained at each time step of the transport code. The ray tracing code uses these profiles to calculate the spatial evolution of the longitudinal wave number spectrum and the energy deposition due to electron Landau damping, collisional damping, and ion cyclotron damping. The wave spectrum is used to advance the electron distribution function in a quasilinear calculation. The effects of the DC electric field and runaway electrons are included in the model for appropriate parameter regimes.

We find that this model can satisfactorily reproduce some major aspects of the Versator II[3] and PLT current drive experiments, with the density threshold phenomenon as a notable exception. Simulations of ion heating experiments recently performed on Versator II indicate that heating efficiency may be quite sensitive to the details of the collisional absorption of rays in the cold outer plasma region. This result may explain the variability of efficiencies reported in past experiments.

* Work supported by U.S. Department of Energy

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A Sufficient Condition for Stability of Axisymmetric Collisionless Systems*

A. E. Walstead
Physics Department, University of California
Los Angeles, California 90024 U.S.A.

A sufficient condition for stability of an axisymmetric mirror is obtained based on an improved approximation to the Kruskal-Oberman (KO) energy principle. The stabilizing effect of plasma compression, contained in the so-called kinetic contribution to the KO potential energy functional, is approximated by a positive definite lower bound. The resulting functional is minimized in the high azimuthal mode number limit and yields an integro-differential eigenvalue problem. The final criterion involves the solution of an auxiliary eigenvalue problem for the lowest two eigenvalues λ_o and λ_1. Whereas previous criteria yield stability only if $\lambda_o \geq 0$, the new criterion yields stability when $\lambda_o < 0 < \lambda_1$ provided $\oint d\ell G\phi/B \geq \alpha$, where G and α are given functions of the field geometry and pressure profiles, and ϕ is the solution of a simple boundary value problem. The criterion is applied to a model configuration consisting of a simple mirror with stabilizing internal ring current. Stability is shown to obtain for an enlarged class of pressure profiles that are weakly increasing functions of flux and for which conventional analysis predicts instability.

*Work supported by DOE and NSF.

TOROIDAL MOMENTUM DISSIPATION IN BEAM-INJECTED PLASMAS*

J. Hogan

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Mechanisms are being sought to explain the rapid dissipation of toroidal momentum in tangential beam injection experiments in tokamaks. A possible model is pursued here: the enhancement of radial diffusion of toroidal momentum toward regions of high charge exchange loss by means of sawtooth oscillations. The classical multiple time scales analysis of relaxation to perpendicular transport is carried out following Shafranov's analysis for thermal conductivity.[1] The justification for such a classical calculation in the present context is that trapped particle effects are small, and collisionality high, near the axis where the toroidal flow velocity is maximum; further, previous kinetic estimates[2] are that the kinetic terms are $q^2 \times$ larger than the classical off-diagonal components of the stress tensor. Of course, $q^2_{axis} \approx 1$. The advantage of a fluid calculation is that flows with $v/v_T \sim O[(\rho_i/_L)^o]$ are admitted, and these may be relevant to some present experiments.

The analogous "Pfirsch-Schlüter" factor for momentum transport is thus obtained, but the key result is the entrainment of toroidal flow in the magnetic surfaces by the parallel viscous force. Fast reconnection processes thus rearrange v_ϕ/r adiabatically and large scale islands produce contributions of parallel and gyroviscous momentum transport to the (relatively small) classical perpendicular flux. Estimates are presented of enhanced momentum transport which is caused by magnetic flux rearrangement (in the Kadomtsev model) caused by sawtooth oscillations and by large scale islands.

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*Research sponsored by the Office of Fusion Energy OER, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

[1]V. D. Shafranov, Plasma Phys. 8, 314 (1966).

[2]R. D. Hazeltine, Phys. Fluids 17, 961 (1974).

POSTER SESSION

NEUTRAL BEAM INJECTION AND PLASMA INSTABILITIES DUE TO ANISOTROPY*

D. K. Bhadra, S. C. Chiu, and R. W. Harvey
General Atomic Company
San Diego, California

ABSTRACT

Present-day tokamaks are using a large amount of beam power (injected either parallel or perpendicular to the toroidal magnetic field) in order to achieve plasma heating. Such anisotropic injection of energetic beam may drive certain plasma modes unstable. We consider near-perpendicular neutral beam injection in a tokamak and obtain the ion distribution function using a numerical Fokker-Planck code. The distribution function is radically altered from a Maxwellian during the early phase of injection and remains non-Maxwellian. Such distribution functions are found to be susceptible to the excitation of magnetoacoustic cyclotron modes, particularly in the presence of a significant number of magnetically trapped energetic ions. The range of physical parameters is explored where such an instability occurs with growth rate $\gamma \sim 10^{-2}\ \Omega_i$ (Ω_i is the ion cyclotron frequency). The quasi-linear relaxation of high energy ions is studied in the presence of such instabilities in order to understand anomalous beam spreading, isotropization and scattering losses.

*Work supported by Department of Energy Contract DE-AT03-76ET51011

POSTER SESSION

STUDY OF LOWER HYBRID ION HEATING WITH/WITHOUT NEUTRAL BEAM INJECTION*

M. Rosenberg, S. C. Chiu, and C. S. Liu
General Atomic Company
San Diego, California

ABSTRACT

We study a mechanism for the production of a hot-ion tail distribution by lower hybrid waves in a tokamak plasma with/without neutral beam injection.[1] A quasi-linear equation for the hot-ion distribution is used: it includes diffusion due to the lower hybrid waves, as well as collisional diffusion, and collisional drag. The rf diffusion coefficient incorporates the lower hybrid dispersion relation, the resonance condition $\omega = \underline{k}_\perp \cdot \underline{v}_\perp$, and is proportional to the rf power. For a lower hybrid $k_\parallel$ spectrum which is $\propto$ (const/$k_\parallel$), a Maxwellian solution in perpendicular energy is obtained for the hot-ion distribution f, $\ell n\, f \propto -(E_\perp/T_{eff})$, with an effective temperature T_{eff} proportional to the rf power. Recent experimental results on lower hybrid ion heating with/without neutral beam injection indicate such behavior. We also study the possibility of enhanced reactivity for a fusion reactor.

[1]"Study on LHW on JIPP TII," presented at U.S.-Japan Joint Conference on Current Drive and Ion Heating of Lower Hybrid Heating, Tokyo, 1981.

*Work supported by Department of Energy Contract DE-AT03-76ET51011

THEORY AND SIMULATON OF QUASIOPTICAL GYROTRONS AND KLYSTROGYROTRONS*

Anders Bondeson[a], Baruch Levush[a], Wallace M. Manheimer[b], and Edward Ott[a,b]

[a] Laboratory for Plasma and Energy Studies
University of Maryland, College Park, Maryland 20742

[b] Plasma Theory Branch, Plasma Dynamics Division
Naval Research Laboratory, Washington, D.C. 20375

Very high power sources for mm wavelength radiation are desired for cyclotron heating of magnetic fusion devices. To meet this goal a quasioptical gyrotron has been proposed and analyzed from a single mode approach.[1] In this work a more realistic analysis of the quasioptical gyrotron is carried out using multimode time-dependent simulations to study mode competition in a highly overmoded cavity. We find that with suitable contouring of the dc magnetic field, single mode operation at $\geqslant 30\%$ efficiency is possible. To further improve on efficiency, a new configuration, the quasioptical gyroklystron, is proposed and analyzed using single mode steady state theory and multimode dynamic simulations. The klystron is shown to lead to a significant increasing in efficiency ($\approx 45\%$), particularly at moderate values for the high frequency electric field.

Similar analyses of the quasioptical gyrotron and gyroklystron operating on the second harmonic have shown promising results; efficiencies $\approx 30\%$ have been obtained for the klystron configuration.

*Work supported by the Office of Naval Research at the University of Maryland and by Department of Energy at the Naval Research Laboratory.

[1]P. Sprangle, W. M. Manheimer, and J. L. Vomvoridis, Phys. Rev. A23, 3127, 1981.

Poster

ION CYCLOTRON RESONANCE HEATING IN A STRONGLY INHOMOGENEOUS MAGNETIC FIELD*

B. D. Fried, K. Nozaki**, G. Morales and A. Fukuyama†
Department of Physics, University of California
Los Angeles, California 90024 U.S.A.

To understand the effects of strong magnetic field inhomogeneities (characteristic of multipoles and high beta mirrors) on ion cyclotron resonance heating, we have analyzed the single particle response to an r.f. field using a model magnetic field, $B_z(x) = B_o \exp(\kappa x)$, for which all results can be obtained in closed form. Ions with total energy $W = mv^2/2$ execute periodic closed orbits with a cyclotron frequency Ω, about a guiding center drifting in the y direction with speed $V_D = (\omega_o - \Omega)/\kappa$ where $\omega_o = eB_o/mc$, $\Omega = \omega_o(1 - h^2)^{1/2}$ and $h = \kappa v/\omega_o \leq 1$. (Ions are unconfined for $h > 1$). The orbit in the guiding center frame, $X = \kappa x - \log(\Omega/\omega_o)$, $Y = \kappa y - (\omega_o - \Omega)t$, is $X = \log [\Omega/\omega_o(1 + h\cos\theta)]$, $Y = \theta - \psi$, where $\theta = \Omega t$ and $\psi = 2\tan^{-1} \{[(1 - h)/(1 + h)]^{1/2} \tan (\theta/2)\}$. In an r.f. electric field of frequency ω, ions with $\Omega = \omega$ will gain energy, but as they do so, the energy dependence of Ω causes them to drop out of resonance, resulting in a super-adiabatic behavior, with no time-averaged energy gain. Since the motion is anharmonic, similar behavior occurs at each of the harmonic resonances, $\omega = n\Omega$, where n is any integer. However, for r.f. field amplitudes above a critical value E_c which is a function of ion energy given by $E_c = [m\omega^2/8e\kappa n(n+1)^2]\ [(1 + \Omega/\omega_o)/h]^n$ for left-hand circular polarization, these resonances overlap, resulting in stochastic heating.

*Research supported by U.S.D.O.E.

**Department of Physics, Nagoya University, Nagoya 464, Japan
†Department of Electronics, Okayama University, Okayama 700, Japan

ORAL PRESENTATION REQUESTED.

A 3-D Model for Computing Self-Consistent Transport Dominated Tandem Mirror Equilibria*

David V. Anderson
National Magnetic Fusion Energy Computer Center
Lawrence Livermore National Laboratory
Livermore, California

Many 3D mirror equilibria previously calculated have used accurate coil fields but have used idealized pressure functions for representing the plasma. Studies of the transport and stability of these equilibria might not be relevant to experiments or reactors because the configurations could not be assured to be realistic or optimal. We compute the 3D electrostatic guiding center equilibria in flux line (α, β, z,) coordinates and obtain pressure functions self-consistently from the steady state solutions of the bounce-averged Fokker-Planck equations computed on these same field lines. The use of flux line coordinates gives several other advantages such as preserving $\nabla \cdot B = 0$, being the preferred coordinate system for subsequent stability studies, and allowing an optimal distribution of gridpoints. Both the Fokker-Planck problem and the equilibrium problem generate implicit parabolic and elliptic systems which we solve with vectorizable sparse matrix techniques.

*Work performed under the auspices of the U. S. Department or Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

Would prefer Poster Session.

POSTER SESSION

TRANSPORT IN TOKAMAK PLASMAS WITH ARBITRARY TOROIDAL ROTATION*

F. L. Hinton, S. K. Wong, and K. H. Burrell
General Atomic Company
San Diego, California

ABSTRACT

A fluid description is given of particle and energy transport in a pure plasma which is rotating toroidally. The rotation velocity is assumed to be of the same order as the ion thermal velocity. The theory is formulated in general geometry. The outward shift of the density, due to centrifugal force, is calculated. A relatively large poloidal electric field is required to enforce quasineutrality. The effect, of the density and potential variation on a magnetic surface, on the particle and energy flux is calculated. The particle flux depends upon the radial gradient of the angular velocity of rotation, as well as the gradient of the magnetic-surface averaged density. The ion heat flux is increased somewhat by the toroidal rotation.

*Work supported by Department of Energy Contract DE-AT03-76ET51011

2E14

NON LINEAR INTERACTION OF TOROIDICITY-INDUCED DRIFT MODES

P.L. Similon and P.H. Diamond
Institute for Fusion Studies
University of Texas
Austin, Texas 78712

The unstable low frequency microfluctuations which exist in toroidal geometry (the electrostatic toroidicity induced (TI) and slab-like (SL) drift modes) are studied in their non linear regime, using a non linear ballooning representation. The renormalized equation allows the determination of the non linear coupling of the various modes due to Compton Scattering.

It is shown that, due to the large spatial extent of the modes along the field lines, the interaction of modes of neighboring perpendicular wave numbers ($k_\perp$) is small. On the other hand, there is a large transfer of energy from modes of large to small $k_\perp$ (distant interaction), which results in an efficient non linear stabilization of high $k_\perp$ modes. The non linear frequency shift is associated to a modification of the eigenmode structure and of the convective damping.

Besides the source of energy (the electrons which excite the T. I. modes), the various sinks are identified: the electrons (for the low $k_\perp$ modes with $\omega > \omega_e^*$, the electron diamagnetic frequency), and the ions (convective damping, and coupling to the slab-like branch).

Finally, for a specific excitation model (trapped electron response), the fluctuation saturation level and transport coefficient are estimated.

Work supported by DOE Grant No. DE-FG05-80ET-53088.

<u>Oral Session</u>

NONLINEAR EVOLUTION OF A SINGLE TEARING MODE ISLAND

Ken Swartz and R.D. Hazeltine
Institute for Fusion Studies
University of Texas
Austin, Texas 78712

The eventual nonlinear effects of tearing mode growth usually depend upon such multiple-helicity effects as island overlap and stochasticity. However, under pre-disruptive conditions, single tearing mode islands, with definite helicity, can evolve to significant width. The single island problem is here analyzed using kinetic theory. Previous studies[1-2] have shown that in the collisionless limit the magnetic island saturates at the linear current channel width, while in the collisional regime, and for larger amplitudes, the island grows linearly in time. A nonlinear equation, and approximate analytic solution, for the island width is presented; it is uniform in the collision frequency, reproduces the previous limits, and shows sharply retarded growth once the island width exceeds the relevant tearing layer width. The use of flux coordinates appropriate to the altered field topology greatly simplifies the analysis. Furthermore, many generalizations are possible with this formulation. We present an equation for the island evolution, valid for arbitrary orderings of the effective growth rate, island orbit frequency and collision frequency. The new formulation also allows straightforward investigation of such potentially important effects as cross-field convection, equilibrium gradients, and large ratios of the island width to the ion gyroradius.

1. Drake, J.F. and Lee, Y.C., Phys. Rev. Lett. 39, 453 (1977).
2. Rutherford, P.H., Phys. Fluids 16, 1903 (1973).

Work supported by DOE Grant No. DE-FG05-80ET-53088.

2E16

THE DYNAMO EFFECT IN THE REVERSED-FIELD PINCH*

R. K. Keinigs and R. A. Gerwin

Los Alamos National Laboratory

Los Alamos, New Mexico 87545

The anomalously long sustainment phase of the reversed toroidal field in the Los Alamos ZT-40 experiment may be due to a turbulent electromotive force, or "α-effect." Several aspects of this effect will be discussed.

1. $\vec{E}$(turb.) can be expressed in terms of a weighted integral of the current helicity spectrum by specifying the statistical properties of the magnetic fluctuation spectrum.

2. Results of (1) indicate that compressibility may play a role in the α-effect.

3. Initial specification of the statistical properties of the velocity fluctuations (including compressibility) provides a means of estimating the level of density fluctuations necessary for amplification of the mean magnetic field.

4. In a cylindrically bounded system there can exist a "cross-field" α-effect, which can produce amplification of field profiles near the magnetic axis.

*Worked performed under the auspices of the USDOE.

2E17

Correlation Functions for Noisy Nonlinear Maps*

J. C. Whitson** and S. P. Hirshman
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

ABSTRACT

A path integral equation formalism is developed to obtain the frequency power spectrum of nonlinear maps exhibiting chaotic behavior. The logistic map $x_{n+1} = 4\lambda x_n(1-x_n)$, for $0 \leqslant \lambda \leqslant 1$, is studied in detail as a paradigm of systems whose exact dynamics are exceeding complex, but which nevertheless possess well-behaved solutions in the presence of small sources of external noise. A Boltzmann integral equation is derived for the probability distribution function p(x,n). This equation is linear and therefore amenable to spectral analysis. The nonlinear dynamics of the map appear as transition probability matrix elements and the presence of noise is manifested by overall multiplicative factors. This formalism is used to investigate the band structure of the logistic map and to analyze the effects of noise on the invariant measure and power spectrum.

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**UCCND Computer Sciences, Oak Ridge, Tennessee.

ORAL

2E18

Transport, End Loss, and Ambipolarity in Tandem Mirrors

Peter J. Catto and J. R. Myra

Science Applications, Inc.
Plasma Research Institute
934 Pearl Street
Boulder, Colorado 80302

Soon after the introduction of the tandem mirror concept the importance of ion radial transport became evident. In order that the gain achieved by electrostatic end plugging not be compromised, it is presently felt that the success of the tandem mirror as a viable fusion reactor depends, at least in part, on keeping the radial center cell ion losses small compared to center cell ion end losses. However, because the radial particle (and energy) fluxes depend on the radial variation of the electrostatic potential Φ, while the end losses depend on Φ via the barrier heights along the magnetic field, a self-consistent prescription for determining the relevant potential profiles is necessary. Such a determination will in general also depend on both the electron transport and symmetry of the device. Retaining the appropriate end and radial losses, a 1-D, self-consistent model of ambipolar tandem mirror operation is obtained which allows a comparison between several idealized modes of operation in order to determine optimal conditions.

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*Work supported by the U. S. Department of Energy under contract DE-AC03-76-ET-53057 with Science Applications, Inc.

POSTER SESSION

CALCULATION OF ISLAND SIZE DRIVEN BY AN EXTERNAL SOURCE*

J. K. Lee, H. Ikezi, T. H. Jensen, and N. Ohyabu
General Atomic Company
San Diego, California

ABSTRACT

An island can be formed by an external perturbation as well as by a resistive instability. Such external perturbations may include an error field caused by gaps in the conducting shell, irregular coil shapes, errors in the installation of coils, or a field produced by an external helical coil. The size of an island due to an external source is calculated from the linear perturbation of the radial magnetic field including the plasma response. The analysis is performed only for tokamak equilibrium profiles which are stable (i.e., $\Delta' < 0$) with the assumption of a large aspect ratio, a circular cross-section, and a zero-β. The calculated island size is sometimes larger when the plasma response is included. The significance of the plasma response depends on the equilibrium profile, but the enhancement is largest for cases where Δ' is close to marginal stability.

*Work supported by Department of Energy Contract DE-AT03-76ET51011

STABILIZATION OF TANDEM MIRROR TRAPPED PARTICLE MODES BY INCOMPLETE CANCELLATION OF PARTICLE DRIFTS*

L. D. Pearlstein, D. E. Baldwin, R. H. Cohen, T. K. Fowler, and B. G. Logan
Lawrence Livermore National Laboratory, University of California
Livermore, California 94550

A curvature-driven, electrostatic trapped particle mode important in tandem mirrors has recently been discovered by Rosenbluth, et al.[1] The mode is sensitive to the fraction of particles passing between regions of good and bad magnetic curvature, becoming severe in configurations having a small fraction of such particles. In these devices, the lowest order bounce-averaged drifts can vary with charge, energy, and pitch angle. Differences between the electron and ion drifts can stabilize the simple zero-frequency trapped particle mode by conversion to a drift wave. One source of such an effect is the unequal axial extents of ion and electron bounce orbits implicit with electrostatic confinement in open magnetic geometry. Another is the elimination of the perturbed ExB response of an energetic electron subpopulation, such as occurring in a thermal barrier. Configurations that can be made stable by this means will be presented.

1. M. N. Rosenbluth, H. L. Berk, H. V. Wong, D. E. Baldwin, and T. Antonsen, "Fast-Growing Trapped Particle Modes in Tandem Mirrors". Paper to be presented at the 1982 Sherwood Meeting--Annual Controlled Fusion Theory Conference, Santa Fe, NM, April 25-28, 1982.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

Second Order Hamiltonian for Guiding Center Particle Motion

D. C. Stevens and H. Weitzner
Courant Institute of Mathematical Sciences
New York University

ABSTRACT

The motion of a charged particle in a given magnetic field is simplified by the introduction of the magnetic moment adiabatic invariant. The magnetic moment is given as an asymptotic expansion in the parameter ϵ, the ratio of Larmor radius to magnetic field scale length. In addition to the magnetic moment, one also obtains the Hamiltonian for the bounce and drift motions. We carry out the construction of Hamiltonian correct through second order for the special case applicable to nearly axisymmetric configurations with the poloidal magnetic field of order one in ϵ, the toroidal field no larger than order one, and the perturbing non-axisymmetric field of order ϵ. In this case no longitudinal invariant exists for passing particles, (H. Weitzner, Phys. Fluids 24 (12), 2280-2294 (1981)), and Hamiltonian to high order accuracy may be needed to decide whether passing particles are truly confined.

A computational algebra program (named PFSA for program for simple algebra) has been written by Stevens and has been applied to do the above described determination of the Hamiltonian. A description of PFSA may be obtained on the MFE network by: FILEM READ 1540 .ALGEBRA W. After the generator of the contact transformation was determined, a run to compute the Hamiltonian takes 6 minutes on the Cray. The problem is far too big for Macsyma.

This work was supported by the U.S. Department of Energy Contract No. DE-AC02-76ER03077 and the Air Force Office of Scientific Research Contract No. 76-2881.

Poster Session preferred, not on Monday

1982 Sherwood Meeting
Sante Fe, New Mexico
April 25-28, 1982

ANTENNA-PLASMA COUPLING THEORY FOR ICRF HEATING*

A. Ram and A. Bers
Massachusetts Institute of Technology
Plasma Fusion Center
Cambridge, Massachusetts 02139

We present a linear theory of coupling of waves in the ion-cyclotron range of frequencies (ICRF) to a plasma of large minor radius where the analysis can be carried out in a slab geometry. The waves are excited by a finite size current sheet antenna protected from the plasma by an anisotropic metal sheet. The plasma is modelled by its cold dielectric tensor with inhomogeneous density and applied toroidal magnetic field. We consider the excitation of only the fast wave component of the ICRF wave. We show how the resistive contribution to the radiative impedance of the antenna is a function of the edge-plasma density and its gradient. The reactive part is found to be equivalent to solving the problem of the antenna in a finite-sized box of purely conducting walls. The resistive impedance and the power coupled into the plasma depend significantly on the phasing of a set of antennas in the poloidal direction.

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Stability of Compact Torus - Ion Ring Hybrid Systems to Non-Axisymmetric Modes

A. D. Turnbull and R. N. Sudan
Laboratory of Plasma Studies, Cornell University, Ithaca, NY 14853

The stabilizing influence of a high energy finite gyroradius ion component on the tilting mode of a spheromak has previously been demonstrated[1] in the case where the beam has only a first order effect ($\varepsilon \sim I_b/I_p$) on the equilibrium. An extension of that work to include general non-axisymmetric modes in an arbitrary compact torus geometry has since been presented.[2] The present paper provides a further extension of the theory to include betatron resonance effects by adopting a less restrictive scaling. Numerical results are presented from a new computer code designed to compute general compact torus-ion ring equilibria and to calculate δW for any given perturbation of the equilibrium. The equilibrium solver is adapted from one developed at Cornell.[3] δW includes all beam and plasma contributions but presently does not include betatron resonances. The results for a tilt mode in a spheromak indicate that when the beam current is moderate (compared to the plasma current), the direct contribution to δW resulting from perturbations of the beam is less stabilizing than a simple extrapolation of the first order theory would predict. However, the indirect stabilization resulting from the modified plasma δW (that would be obtained if the beam were rigid[4]) is enhanced, so that stabilization of the tilt mode of the spheromak appears to be possible.

This work supported by U.S. Department of Energy Contract DE-AS02-76ET53065.

1. R. N. Sudan and P. K. Kaw, Phys. Rev. Lett. 47, 575 (1981).
2. A. D. Turnbull and R. N. Sudan, Bull. Am. Phys. Soc. 26, 888 (1981).
3. J. M. Finn and L. Sparks, Cornell Univ. LPS Report 230 (1977).
4. J. L. Johnson, R. M. Kulsrud, and K. E. Weimer, Plasma Physics 11, 463 (1969).

RESTRICTED MULTIPLE THREE-WAVE INTERACTIONS*

C. R. Menyuk, H. H. Chen, and Y. C. Lee
Laboratory for Plasma and Fusion Energy Studies
University of Maryland
College Park, Maryland 20742

Restricted multiple three-wave interactions, in which a set of resonant triads interact through one shared wave, have been proposed as a model for plasma wave and ocean wave turbulence.[1,2] Paradoxically, it has also been proposed that this system may be completely integrable.[3] We have examined these questions both analytically and numerically. Except in the case when all coupling coefficients are equal, numerical results and Painlevé analysis indicates that the system is nonintegrable; in the case where all the coupling coefficients are equal, we have found the Lax pairs for the system. We have also investigated the validity of the R.P.A. for this system and its relation to the Gibbs ensemble.

*Work supported by National Science Foundation.

[1]K. M. Watson, B. J. West, and B. I. Cohen, J. Fluid Mech. 77, 185 (1976).
[2]J. D. Meiss, from "Nonlinear Properties of Internal Waves" Workshop in LaJolla, CA, 1981.
[3]J. D. Meiss, Phys. Rev. A 19, 1780 (1979).

Poster

HAMILTONIAN FORMULATION OF FIELD LINE FLOW

Robert G. Littlejohn
Center for Plasma Physics and Fusion Engineering
University of California
Los Angeles, California 90024

and

John R. Cary
Institute for Fusion Studies
University of Texas
Austin, Texas 78712

The fact that magnetic fields are divergence free implies the existence of KAM surfaces, the absence of attractors, the conservation of an integral invariant by the flow, and a version of Noether's theorem. These characteristics of field-line flow are shared by Hamiltonian systems. These facts motivate this work, in which we present a generalized form of mechanics that contains as special cases, both field line flow and Hamiltonian mechanics.

Perturbation theory for this system of mechanics has been developed[1] and applied to near-integrable systems. Unlike ordinary perturbation theory, this theory preserves the Hamiltonian nature of the flow to all orders. We apply this theory to nearly axisymmetric toroidal magnetic field configurations, such as a tokamak with additional helical coils for the creation of an ergodic divertor.[2] This general theory allows us to calculate the island structure of this system without making the cylindrical or near-cylindrical approximation.

1. Robert G. Littlejohn, Center for Plasma Physics and Fusion Engineering Report PPG-597 (University of California, Los Angeles, 1981).

2. W. Feneberg and G.H. Wolf, Nuclear Fusion 21, 669 (1981).

Work supported by the U.S. Department of Energy Contract No. DE-FG05-80ET-53088 and DE-AM03-76500010 PA 26, Task I, AND contract #.W-7405-ENG-48

ABSTRACT SUBMITTED TO
SHERWOOD THEORY MEETING
1982

PACS #52.65

Suggested Session:
Plasma Simulation

A Comparison of Small vs. Large Angle Scattering in Magnetized Plasmas.* A. Andrade, T.A. Oliphant, Los Alamos National Laboratory and T. Kammash, U. of Michigan -- A comparison of the effects of small vs. large angle scattering phenomena on the transport of charged particles in magnetized plasmas is made via computer simulation. These effects are investigated for a variety of plasma densities and temperatures so that regimes in which the computer time step is controlled by the characteristic slowing down times as well as regimes in which the cyclotion period becomes the smallest time scale are both examined. In the low density regime, a D-D plasma which typifies that of an advanced fuel mirror reactor is used as an example. The basic methodologies that are used in this implicit Monte Carlo simulation are described in Refs. 1 and 2.

1. A. Andrade, Ph.D. dissertation, The University of Michigan, 1981.
2. D. Driemeyer, G. Miley, and W. Condit, "A Monte Carlo Method for Calculating Fusion Product Behavior in Field Reversed Mirrors," presented at the Topical Meeting of Comp. Methods in Nuclear Engineering,1979.

* Work supported by U.S. DOE Contract #W-7405-ENG.36

(Prefer Poster Session)

A. Andrade
A. Andrade
Los Alamos

THE CURRENT QUENCH PHASE OF A PLASMA DISRUPTION*

Y-K. M. Peng, D. J. Strickler and J. A. Holmes
Fusion Engineering Design Center, Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Computational methods are outlined for solving a set of equations modelling the current quench following a disruptive plasma energy loss in a tokamak. The thermal quench phase of a disruption is characterized by a sudden decrease in confinement time in a circular plasma with a uniform current density and these assumptions lead to a set of initial conditions for the simulation. A simplified plasma energy balance equation is solved for a change in the energy (ω_p), leading to a change in the plasma position (R_p) and size (a_p) through the equilibrium relationship,

$$\sum_i G_i I_i = \frac{\mu I_p}{4\pi R_p}\left[\ell n \frac{8 R_p}{a_p} + \frac{8 \omega_p}{3\mu R_p I_p^2} - \frac{5}{4}\right] ,$$

and the plasma interaction with a limiter. The coil currents (I_i) are related to the vertical field necessary for plasma MHD equilibrium through the Green's function G, depending on the plasma position, and are advanced in time by solving a set of circuit equations, coupling them to the plasma current (I_p) and a simulated chamber vessel. A decrease in the plasma minor radius following the disruptive energy loss results in a decrease in the plasma current through the assumption of flux conservation

$$q = \frac{2\pi a_p^2 B_\phi}{\mu R_p I_p} = \text{constant} .$$

The details of this model are presented together with methods of solution and computational experience.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

Stability of Thermal Barriers in Tandem Mirrors

C. Litwin and R. N. Sudan

Laboratory of Plasma Studies, Cornell University, Ithaca, NY 14853

Thermal barriers are designed to separate hot electrons in the endplug from the central cell in tandem mirrors. This is achieved by confining a population of energetic electrons at the bottom of a magnetic well which creates a local depression of electrostatic potential. The anisotropic electron population is susceptible to the whistler mode instability. The interaction between whistlers and particles leads then to diffusion in velocity space. In the presence of an external source of energetic particles (Electron-Cyclotron Resonance Heating - ECRH) and a loss cone, a steady state can be achieved. We find the steady state distribution function by solving the quasilinear diffusion equation and analyze its linear stability properties. Power estimates obtained in this approach are generally lower than the simple-minded ones based on a bi-Maxwellian distribution function, but still larger by at least an order of magnitude than those based on Fokker-Planck calculations. For the density of $5\cdot10^{12}$ cm^{-3}, the magnetic field of 8 kG, parallel temperature $T_{||}$ = 15 keV and the anisotropy factor of 4 the required ECRH power is of the order of 10^2 W/cm^3.

This work supported by U.S. Department of Energy Contract DE-AS02-76ET53065.

2E29

PARAMETRIC DECAY IN A STRONGLY INHOMOGENEOUS MEDIUM

K. Ko, A. Reiman*, K. Papadopoulos**

Science Applications, Inc.
McLean, Virginia 22102

The linear stage for the steady-state evolution in two dimensions of the three-wave parametric decay in a strongly inhomogeneous medium is considered. The interaction can be reduced to the standard coupled system of equations for the case of a linear gradient by an amplitude modulation of an Airy function. The coupling coefficients and group velocties now become spatially varying and the dephasing is no longer quadratic. The effect of strong inhomogeneity on convective and absolute growth are studied numerically.

* PPPL, Princeton, NJ 08544
** University of Maryland, College Park, MD 20742

Work supported by NRL under contract N00173-80-C-0194

Radiation Cooling Instability in Z>1 Edge Plasmas*

L. Montierth, R. L. Morse, G. W. Sowers
Department of Nuclear and Energy Engineering
University of Arizona

An instability driven by radiation cooling of a plasma has been investigated using linearized fluid equations and tabulated corronal radiation rates [1]. The object of this investigation is to understand behavior of Z>1 edge plasmas produced in torroidal systems by puff filling, for the purpose of removing heat. The selfconsistent zero order temperature profiles used depend only on the co-ordinate, $X_\perp$, perpendicular to $\bar{B}$. The zero frequency modes which have been found are localized near the most strongly radiating region and have maximum growth rates, γ_{max}, and marginally stable wave numbers parallel to $\bar{B}$, k_{llmax}, which increase linearly with ion density in the low density ($\omega_i \tau_{ii} < 1$) region. For argon, which has been considered for this heat removing role [2], and $n_i = 10^{13}$ is found that $\gamma_{max} = 2.5 \times 10^4 \text{ sec}^{-1}$ and $k_{max} = 1.2 \times 10^{-1} \text{cm}^{-1}$. It is expected that the density fluctuations caused by this instability will saturate at large amplitudes, i.e., $\delta n/n \simeq 1$, and should, therefore, be observable.

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*Supported by USDOE

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Ballooning and Ideal MHD Stability for the BYU Topolotron

D. L. Peterson

Brigham Young University

A modified version of the General Atomic ballooning code 'MBC'[1,2] has been implemented to study the stability properties of equilibrium solutions to the Grad-Shafranov equation appropriate for the BYU Topolotron experiment. The code has been adapted to handle the Topolotron equilibrium configuration which requires two sets of nested surfaces carrying toroidal plasma current in opposite directions. Analysis is now possible of the stability of Topolotron equilibria to both ideal and resistive interchange, and to ballooning modes following the Connors, Hastie, and Taylor formalism[3] for finite and infinite mode numbers.

Solutions with simple pressure and current profiles produced by the Topolotron equilibrium code have been evaluated for marginal stability, and stable low β equilibria have been found to exist. Adjustments of the plasma shape and aspect ratio have indicated that higher β values can be found. Representative samples of the equilibria studied will be presented with comparisons to results from studies done for other confinement devices.

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2E33

Critical Pressure for Equilibrium and Stability in a Toroidal Stellarator Revisited*

K. E. Weimer, J. L. Johnson, and J. M. Greene
Plasma Physics Laboratory, Princeton University
Princeton, N.J. 08544

Results reported in some recent Russian papers[1] on the critical pressure for equilibrium and for stability in a toroidal stellarator disagree with conclusions drawn in our earlier work.[2] Notably, for certain pressure profiles, Kovrizhnykh and Shchepetov find no upper limit on the pressure. We reexamine our vintage study and discuss these differences.

*This work was supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

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Poster Session

EIGENMODE EQUATIONS FOR AXISYMMETRIC HOT ELECTRON PLASMAS*

T. M. Antonsen, Jr., and Y. C. Lee
Laboratory for Plasma and Fusion Energy Studies
University of Maryland
College Park, Maryland 10742

We derive low m, eigenmode equations for low frequency modes in a bumpy cylinder with a hot electron ring. By exploiting the small parameter Δ/R, where Δ is the ring thickness and R is the radius of the cylinder, we are able to reduce the two dimensional eigenvalue equations to an system of ordinary equations whose independent variable is the magnetic flux. Included in our analysis are the effects of drift resonances for ring particles and bounce resonances for core particles which can give rise to resonant growth of negative energy modes.

*Work supported by the U.S. Department of Energy.

A SELF-CONSISTENT ECRH POWER DEPOSITION CALCULATION FOR TANDEM MIRROR END PLUGS*

D.G. Braun and G.A. Emmert

Fusion Engineering Program
Nuclear Engineering Department
University of Wisconsin
Madison, Wisconsin 53706

Absorption of ECRH power is a function of plasma density and temperature, and often is highly localized. An accurate analysis requires a ray tracing code to calculate the radial power absorption for changing plasma parameters. Such a routine has been added to a transport code (TAMBAR)[1] and the role of ECRH during startup examined. Some results will be presented that indicate the effect of plasma parameters on power absorption, and conversely, the effect of power absorption on the evolution of the plasma.

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*Research supported by DOE Contract No. DE-AC02-80ER53104.

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Effects of Noise on the Standard Mapping

Alexander B. Rechester
Massachusetts Institute of Technology

ABSTRACT

Statistical description of systems far from the thermal equilibrium constitute one of the major unsolved problems of modern physics. The fundamental question in this area is how to derive the statistical properties of such systems based on the equations of motion. We have done a detailed analytical and numerical study of the Chirikov-Taylor model which is one of the simplest models in plasma physics. We have shown that it is the presence of noise which makes the description of such a system unique. The effect of noise on physical quantities such as the diffusion coefficient, etc., depends critically on the nature of dynamical orbits. The method used for the solution of this problem is quite general and can be employed for other problems. Some unsolved problems will be presented and discussed.

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Oral presentation

COMPUTATION OF THE VACUUM MAGNETIC FIELD IN A HELIAC GEOMETRY*

A. I. Shestakov and A. A. Mirin
National Magnetic Fusion Energy Computer Center
Lawrence Livermore National Laboratory
Livermore, California

A numerical procedure for the calculation of a three-dimensional vacuum magnetic field is presented. Useful applications are in the design of non-axisymmetric magnetic confinement configurations. Examples are the Heliac or similar fields discussed by Furth et al.[1]

The domain of interest consists of the interior of a torus that is swept out by an "arbitrary" 2-D cross section that is helically wound about a circular axis. The boundary condition is $\overline{B}\cdot\hat{n}=0$, and the toroidal flux is non-zero. For design applications, once the field is computed, it is planned to use a field-line integrator to examine whether nested flux surfaces exist, and to compute the average magnetic well properties.[1] If these are favorable, the skin currents on the conducting shell may be discretized into finite current loops. By an analysis similar to Dommaschk's[2], the skin currents are shown to coincide with contours of the scalar potential χ, ($\overline{B}=\nabla\chi$).

The mathematical task is reformulated into a Neumann problem for χ, which is multiple valued in the toroidal angle, ϕ. The multiple valuedness is removed by expressing $\chi=\chi'(\overline{r})+\phi/2\pi$. Following ideas of Betancourt[3], Laplace's equation and the boundary condition are derived in non-orthogonal coordinates (σ,ϕ,ζ) where σ is a scaled radial coordinate, ζ a poloidal angle and ϕ as above. The usage of (σ,ϕ,ζ) economizes the number of grid points and Fourier harmonics required. In these coordinates, $\sigma=1$ defines the wall.

Both χ' and the coefficients of the equations are Fourier analysed in ϕ, giving a number of coupled 2-D equations in (σ,ζ). It is planned to further Fourier analyse in ζ; the remaining radial derivates will be approximated by finite differences.

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Prefer Poster Session

2E38

ION BERNSTEIN/ION ACOUSTIC MODE COUPLING*

T. Katsouleas, B. D. Fried and G. J. Morales
University of California, Los Angeles, CA 90024

The coupling between electrostatic ion Bernstein and oblique ion acoustic modes in a non-uniform magnetic field near the second harmonic ($\omega = 2\omega_{ci}$) is examined. Reflection, transmission and mode conversion coefficients are calculated for ion acoustic and Bernstein waves incident from the high field side and for ion acoustic waves incident from the low field side. These coefficients are all functions of a single parameter $\lambda^2 \simeq \frac{1}{5} \frac{r_{ci}}{L_{\nabla B}} \left(\frac{T_e}{T_i}\right)^{3/2}$. If $\lambda^2 \lesssim 10$, there is significant mode conversion in each of the above cases, but the damping of the Bernstein wave ($E \propto \exp[-(x/\ell)^{1/2}]$, with $\ell^{-1} \simeq k_{\parallel}{}^2 L_{\nabla B}$) reduces the observable mode converted energy.

The magnetic field scale length is assumed large ($L_{\nabla B} \gg r_{ci}, k_{\perp}{}^{-1}$) and the Vlasov $\varepsilon(\underline{k}, \omega)$ is expanded in $k_{\perp} r_{ci}$ for fixed $k_{\parallel}$ to order $(k_{\perp} r_{ci})^4$, assuming weak damping ($\frac{\omega}{k_{\parallel} a_i} \gg 1 \gg \frac{\omega}{k_{\parallel} a_e}$, $\frac{T_e}{T_i} \gg 1$, $k_{\perp} \gg k_{\parallel}$). The usual replacement of $k_{\perp}$ by $-i\nabla_{\perp}$ gives a wave equation for the electric field of the form $\frac{\partial^4 E}{\partial x^4} - \lambda^2 (x + i\gamma) (\partial^2 E/\partial x^2 + E) = 0$. This represents the acoustic wave if the fourth order term is neglected and the Bernstein wave if the zeroth order term is neglected. The equation is solved by the usual Laplace transform technique. Choosing appropriate contours and using asymptotic methods to evaluate the contour integrals gives the reflection, transmission and mode conversion coefficients.

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Stochastic Transport of High Energy Fusion Products Under Coulomb and Nuclear Scattering in Field Reversed Configurations

J. C. DeVeaux and G. H. Miley
Fusion Studies Laboratory
Univeristy of Illinois
214 Nuclear Engineering Laboratory
103 S. Goodwin Avenue
Urbana, Illinois 61801

Previous studies (1) have shown that close to 45% of 14.7 MeV, D-^{3}He protons, can be absolutely confined in typical FRM (Field Reversed Mirror) plasmas despite the relatively small size of the plasma (plasma radius ~ 2 fp gyroradii). This surprising result lead to the prediction of near-ignited operating conditions for a D-^{3}He fueled FRM. However, recent work (2) has indicated that NES (nuclear elastic scattering) events induce significant perturbations to the confined trajectories of 14.7 MeV, D-^{3}He protons that alter the fp confinement and energy deposition correlations previously calculated for Coulomb slowing down. Ongoing work is focusing on the stochastic calculation of the percent change in fp confinement and heating induced by NES in the closed field region of the FRM.

In order to rigorously estimate the changes in fp confinement and heating, the stochastic transport code, MCFRM, has been upgraded to track a statistically significant sample (~1000 histories) of 14.7 MeV protons as well as their knock-on progeny. A Hill's Vortex model of field reversal is used to simulate the magnetic topography of a FRM, an elongated version of Hill's Vortex is used in some of the MCFRM runs to model fp dynamics in a long-pulsed, quasi-steady, Field Reversed Theta Pinch (FRθP). Spitzer coefficients are used to simulate Coulomb drag and pitch-angle scattering, and a particle pusher is used to track fp trajectories.

The probability of undergoing a NES event is sampled each time step for every particle history from a cumulative probability distribution. The NES data used is taken from the ENDL library at LLNL(3). The knock-on ions resulting from NES events are angularly distributed according to a P_1 approximation which assumes isotropic scattering (in the COM system) together with an anisotropic correction factor involving forward and backward scattering.

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ALFVÉN ION-CYCLOTRON INSTABILITY IN SLOSHING-ION PLASMAS*

Gary R. Smith
Lawrence Livermore National Laboratory, University of California
Livermore, California 94550

ABSTRACT

The Alfvén ion-cyclotron (AIC) instability occurred in the end-cell plasmas of the Tandem Mirror Experiment and degraded ion confinement.[1] Those plasmas were produced by injecting neutral beams nearly perpendicularly to magnetic-field lines. The next generation of tandem-mirror experiments will have oblique injection of neutral beams, producing "sloshing-ion" distributions.

This poster presents numerical results from the first study of AIC instability in a uniform, sloshing-ion plasma. We consider left-circularly-polarized waves propagating along magnetic-field lines ($k_\perp = 0$). The ion distribution is formed by superposing several ion components, $f = \sum_i f_i$, which allows us to include passing and trapped ions in addition to sloshing ions. Each component has a distribution $f_i = F_i(v)G_i(\varphi)$, where v and φ are speed and pitch angle. A tractable numerical problem results if we take $F_i \propto v^{2\ell_i} \exp(-\alpha_i v^2)$, $\ell_i = 0, 1, 2, \ldots$, as the solution of the dispersion relation then contains only a one-dimensional integral (over φ) involving generalized plasma dispersion functions[2]

$$Z_m(z) = \pi^{-1/2} \int_{-\infty}^{\infty} du\, u^m \exp(-u^2)/(u-z).$$

Our method for calculating these functions is discussed.

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2E41

Determination of Particle Transport in Asymmetric Toroidal Devices Using Magnetic Co-ordinates*

G. Kuo-Petravic and A. H. Boozer
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

We present here studies of guiding center drift orbits in the toroidal device HELIAC. As already described elsewhere[1,2], we use a Fourier decomposition technique where the magnetic field strength of any toroidal device may be given in terms of a set of magnetic co-ordinates. A Monte-Carlo[3] code which describes the particle drift motion in the same co-ordinates has been used to yield information on particle transport.

*This work supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

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Poster Session

2E42

MACROSCOPIC STABILITY OF LARGE ASPECT RATIO MIRRORS WITH ENERGETIC PARTICLES*

Y. C. Lee and T. M. Antonsen, Jr.
Laboratory for Plasma and Fusion Energy Studies
University of Maryland
College Park, Maryland 20742

The generalized, low frequency kinetic energy principle is shown to be necessary and sufficient for absolute stability in systems with positive dissipation. When applied to devices with unfavorable curvature such as EBT and STM the principle predicts instability. However, closer examination reveals that situations exist where the unstable modes experience only weak, resonant growth and may be stabilized quasilinearly. We apply the energy principle to configurations where the energetic particles are trapped in a region of favorable curvature and determine their effect on ballooning and interchange modes. In general, the energetic particles have a strongly stabilizing influence on these modes.

*Work supported by Department of Energy.

Oral

2E43

A METHOD FOR CONSTRUCTING THE WKB CONNECTION FORMULAS FOR THE MODE-CONVERSION TUNNELLING PROBLEM

R. J. Kashuba
McDonnell Douglas Corporation
St. Louis, MO 63166

H. L. Berk
Institute for Fusion Studies
Austin, Texas 78712

Physical processes involving mode conversion generally have in addition an evanescent regime hence they also involve tunnelling. Such processes are described by higher than second order equations. The Furry rules modified by Heading are generally adequate to construct the WKB solutions of second order equations. However, there are ambiguities concerning the proper analytic branch when these rules are applied to problems described by higher order equations. We will show how to formulate the rules for these more general problems. A diagrammatic technique will be presented by which the correct connection formula for non-dissipative wave problems can be obtained and energy conservation demonstrated. These rules provide a simple method independent of the detailed structure and avoid complicated contour diagrams. We will discuss the Schrodinger tunnelling problem to explicate the differences with the mode-conversion tunnelling problem. Finally the ICRF mode conversion tunnelling equation with a minority species will be specifically solved.

Numerical Studies of Tandem Mirrors Using Reduced MHD

H. R. Strauss and S. Wollman

Courant Institute of Mathematical Sciences
New York University

ABSTRACT

The design and operation of successful tandem mirror experiments depends in part on reliable predictions of MHD equilibrium and low mode number stability. In general this requires three dimensional numerical computations. Substantial progress has been made using reduced tensor pressure MHD equations of motion [1,2] based on a large aspect ratio $\beta \sim 1$, ordering. We have solved the reduced equations numerically as an initial value problem. The computation proceeds in two stages. First, given a vacuum magnetic field, a pressure balance equilibrium is found both perpendicular and parallel to the magnetic field. Second, the pressure balance equilibrium is the initial state for incompressible transverse, shear Alfven motion. Kinetic energy is removed to force the plasma toward equilibrium. It is found that equilibration proceeds fastest on the longest length scales, with finer length scales requiring longer time. Depending on the plasma parameters, an exponentially growing, predominantly $m = 4$ motion may occur, which can grow to large amplitude.

For 2XIIB vacuum fields, we find the marginal stability point of the $m \approx 4$ mode agrees with the interchange stability criterion at low beta. At higher beta, progressively larger quadrupole magnetic field is required for stability. Stable equilibria have been obtained for beta of at least 0.7.

In the case of tandem mirrors, computations have begun with model vacuum fields, for which it has been possible to obtain stable equilibria with beta of at least 0.25. Computations will be carried out using vacuum fields based on experimental designs.

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FINITE-ORBIT SATURATION OF THE STUPAKOV EFFECT*

William A. Newcomb
Lawrence Livermore National Laboratory, University of California
Livermore, California 94550

According to Stupakov, parallel currents arising in the end sections of a standard tandem-mirror device produce an $m = 4$ distortion in the equilibrium flux surfaces in the center section.[1,2] The amount of distortion is directly proportional to the length L of the center section. If, however, FLR terms are taken into account, the effect may saturate, in the sense of approaching a finite upper limit as $L \to \infty$. This depends on the sign of the quasielastic coefficient Y in the FLR Lagrangian.[3] For positive Y, saturation occurs, and for negative Y, enhancement of the effect, possibly leading to instability.

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ORAL SESSION

Oral Session

3A2

FAST GROWING TRAPPED PARTICLE MODES

M. N. Rosenbluth, H. L. Berk*

D. E. Baldwin**

H. Vernon Wong***

T. M. Antonsen****

It has been proposed that in tandem mirrors, axisymmetric auxiliary mirror cells serving as thermal barriers be interposed between the central solenoidal cell and the quadruple anchor. Because of the effective barrier provided by the axicell, particle densities could be very low ($\sim$ one per cent of central density) in the transition region between the axicell and the MHD anchor. Such configurations, while MHD stable, are unstable to trapped particle modes.[1,2] We find that the instability can grow on MHD time scales rather than on a reduced time scale as is generally characteristic of trapped particle modes. We use a generalization of the trapped particle formalism of Antonsen and Lee[3] to find that the condition for trapped particle modes having MHD growth rates is $N_t/N_c < L_c/L_t(k_\perp^2\rho_i^2)(T_t/T_c)$, where the subscripts t and c refer to the transition region and central cell respectively. The instability is driven by the average unfavorable curvature in the axicells.

The most unstable perturbations appear to be those which are flute-like in the central cell and axicells, but which decrease to zero in the transition region. No bending stabilization arises as in standard MHD theory as the mode is nearly electrostatic with $E_\parallel$ finite. Some stabilization similar to FLR effects occurs due to charge separation resulting from differing electron and ion orbits. The instability may also be sensitive to particle drift variations along the field line, and these effects are currently under investigation.

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* Institute for Fusion Studies, University of Texas at Austin, Austin, Texas

** Lawrence Livermore National Laboratory, Livermore, California

*** Fusion Research Center, University of Texas at Austin, Austin, Texas

**** University of Maryland, College Park, Maryland

PARTICLE SIMULATIONS OF QUASI-LINEAR DIFFUSION IN A NEUTRAL-BEAM-DRIVEN MIRROR MACHINE*

Bruce I. Cohen, Neil Maron, Gary R. Smith, and William M. Nevins
Lawrence Livermore National Laboratory, University of California
Livermore, California 94550

Simulations of drift-cyclotron-loss-cone instability have been performed with a hybrid code that includes ion bouncing in a mirror magnetic field and mirror sources and losses modeling the 2XIIB experiment. The simulation models electrons as a linearized fluid, but the ions are fully nonlinear. Particle ions gyrate and bounce or transit axially, but do not experience ∇B or curvature drifts. The simulation includes a transverse density gradient, axial loss out of the ends of the mirror, ion-electron drag, an axial ambipolar potential profile, charge-exchange with a neutral beam, neutral beam ionization, and stream injection. Electrostatic ion-cyclotron drift and lower hybrid waves are calculated self-consistently in local ($\vec{k} \cdot \nabla n_0 = 0$) and flute ($\vec{k} \cdot \vec{B} = 0$) approximations.

Arising from the joint action of an ion cyclotron wave and axial ion bouncing in the nonuniform mirror field are ion bounce resonances. There are also resonances between the ion-cyclotron wave and the harmonics of the trapping frequency of an ion in the potential well of the wave. These primary and secondary resonances overlap in our simulations, leading to stochasticity and velocity diffusion. Diffusion of ions into the loss cone nonlinearly stabilizes the distribution function, and the drift-cone mode amplitude and the rate of ion end-loss attain steady-state values. Low density simulations with a discrete wavenumber spectrum tend toward a monochromatic wave form. At higher, more realistic densities, saturated wave amplitudes are lower and approach experimental values ($e\tilde{\phi}_k/T_i \lesssim 10^{-2}$); the frequency is more resonant ($\omega \sim \omega_{ci}$); but the wave turbulence becomes multi-mode in character. Electron axial dissipation reduces the turbulence and shifts the spectrum to longer wavelengths. The wave turbulence is generally insensitive to the energy width of the neutral beams, but is sensitive to termination of the neutral beam and to stabilizing plasma stream filling the loss cone. In all cases the available free energy in the ion loss-cone velocity distribution sets an upper bound on the wave energy, with the excess free energy returned by the waves to sustain the ion tail against electron drag. The scalings of wave frequencies and amplitudes with parameters, e.g., $(m_e/m_i + \omega_{ci}^2/\omega_{pi}^2)$, point toward the observations in 2XIIB. These simulations provide a first-principles confirmation of many of the macroscopic and microscopic features of the quasi-linear diffusion model of drift-cone turbulence in mirror plasmas.

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ORAL SESSION

ANALYSIS OF A SIMPLE TRANSPORT MODEL

Philip Rosenau
Dept. of Nuclear Engineering
and
Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

We analyse a simple energy transport model represented by

$$n(x)\partial_t T = \nabla K_{\perp}(T,r)\nabla T + H(T) - R(T) \qquad (1)$$

The following problems are studied.

I. Effects of radiation on nonlinear thermal evolution. It is shown that depending on the functional form of R(T) radiation may cause extinction of a thermal pulse within a finite time, may cause its filamentation and force it to shrink. If an appropriately nonlinear heating mechanism, H(T), is available, a self-confined thermal pulse is formed; it is a stationary solution of Eq. (1) having a finite support and <u>no transfer of heat flux</u> at its edge. This implies that enhanced radiation near the edge of the plasma may reduce the heat load on the wall without negatively affecting the global thermal stability.

II. Various calculations of the average energy needed for ignition and stability of thermo-nuclear reactions are made using the zero-D approach. As a rule, the conductive losses are volumetrically simulated by $\nabla K_T \nabla T \to 3TK/a^2$ or by using τ_E. While the first is imprecise the second may be incorrect. We provide a precise prescription of how to replace surface losses by an energetically equalivalent volumetric sink, e.g., in the case of $\partial_{xx}T$, one uses

$$\partial_{xx}T^n \to -\lambda_* T^n \qquad (2)$$

where λ_* is the first eigenvalue of $\nabla^2 u + \lambda u = 0$, solved in the domain of interest with u=0 on its boundary. A similar prescription applies to the general case of $K_{\perp}$.

ORAL PRESENTATION

RUNAWAY CURRENT SUSTAINMENT BY LOWER HYBRID WAVES*

V. S. Chan, C. S. Liu, D. K. Bhadra,
R. W. Harvey and F. W. McClain
General Atomic Company
San Diego, California

ABSTRACT

Recent LH experiments on tokamaks have shown effective runaway current sustainment by lower hybrid waves with high parallel phase velocity. A mechanism which allows these high phase-velocity waves to interact with slower (10 keV) runaway electrons by the nonlinear excitation of $\omega_p \cos\theta$ waves is proposed. The LH waves generate the anisotropy in the tail (100 keV) electrons which destabilize the slow $\omega_p \cos\theta$ waves. These unstable waves in turn deposit momentum to the slower electrons to sustain a steady state current-carrying runaway distribution. These waves also scatter the energetic electrons in pitch angle giving rise to enhanced cyclotron radiation. An analytic theory and numerical results on the current drive efficiency and the saturated wave spectrum will be presented. The resulting J/P is about 2 amp/watt for PLT parameters consistent with experiment.

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RECENT DEVELOPMENTS IN EBT STABILITY THEORY*

D. A. Spong
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

The EBT device was originally built to test the concept that hot electron rings can produce a local minimum in the magnetic field and stabilize the toroidal core plasma against low frequency flute instabilities. This premise was confirmed by the observed stable, quiescent mode of operation. However, a number of instabilities (some of which are novel to this configuration) can still persist when ring-core coupling effects are taken into account. These include the hot electron interchange, the interacting core interchange, and the compressional Alfven mode. Recently, radially resolved methods have been applied to flute-like models of these instabilities. Ring anisotropy, energy spread, relativistic effects, realistic profiles, and magnetic field models have been examined. Several distinct approaches have been pursued, including Maxwell-drift kinetic, hybrid fluid-kinetic, and gyrokinetic methods; also a variety of geometries have been considered, including slab, z-pinch and cylindrical. These tend to give qualitatively similar results; applying them to the EBT-S data has indicated certain parameter ranges over which disagreement exists. The experiment has also revealed some surprising effects not indicated in the theory such as lower thresholds for the C-T transition and anomalous absorption of energy into the ring near $\omega \sim \omega_{dh}$. A new formulation of the theory which takes into account coupling to the shear Alfven wave and could possibly remove some of the present areas of inconsistency between theory and experiment will be discussed. Experimentally relevant orderings of the bounce and drift frequencies for the three plasma species will be examined which allow tractable equations to be obtained from such a model.

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ORAL SESSION

NEOCLASSICAL TENSOR TRANSPORT MODEL FOR EBT PLASMAS*

M.Z. Caponi, M.A. Iskra, T. Kammash+
TRW, Inc.
Energy Research Center
One Space Park, Redondo Beach, CA 90278

A tensor transport model has been developed to investigate the influence of anisotropy on the macroscopic equilibrium characteristics of an EBT plasma. The anisotropy is assumed to be the result of either RF or anomolous effects that can produce directional heating, or the pitch angle dependence of particle loss rates. In the model, the distribution function is assumed to be bi-Maxwellian to lowest order in aspect ratio.

This distribution is used in the drift kinetic equation to obtain tensor transport coefficients that are valid in the Kovrizhnykh (collisional) and plateau regime. A mobility coefficient is found that occurs only for $T_\perp/T_\parallel \neq 1$ and is related to the gradient of the magnetic field. In addition, the anisotropy dependent coefficients produce an ion flux that decreases as $T_\parallel$ becomes larger than $T_\perp$. This result is in agreement with the fact that for a given energy the passing ions tend to be better confined than trapped ions.

The tensor transport coefficients are utilized in tensor fluid equations derived by taking appropriate moments of the time dependent drift kinetic equation. Independent energy conservation relations are formulated for $T_\perp$ and $T_\parallel$. These equations show the presence of a perpendicular to parallel energy transfer term that depends on the magnetic field geometry and is independent of collisions. Hence, depending on parameters it can either isotropize or further anisotropize the plasma. The self-consistent ambipolar potential is found to decrease with $T_\parallel/T_\perp$, and this dependence increases with the total ion temperature. Thus, it plays an important role for tail ions. For 150 eV ions factor of three variations in the ambipolar potential are found as a result of anisotropy ($T_\parallel/T_\perp \sim .5$). These results, however, are sensitive to the orbit model adopted for the derivation of the transport coefficients. The parametric dependence of the macroscopic equilibrium characteristics as a function of directional heating will be presented.

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+University of Michigan

Equilibrium Poloidal Field Distributions in Reversed Field Pinch Toroidal Discharges

Don Baker, Lawry Mann, Kurt Schoenberg

Los Alamos National Laboratory

A comparison between the analytic formulae of Shafranov for equilibrium in axisymmetric toroidal RFP systems and fully toroidal numerical solutions of the Grad-Shafranov equation is presented as a function of poloidal beta, internal plasma inductance and aspect ratio. The Shafranov formula for the equilibrium poloidal field distribution is accurate to within 5% for aspect ratios greater than two, poloidal betas less than 50% and for plasma current channels that exceed one third of the minor toroidal radius. The analytic description for the center shift of the innermost flux surface that encloses the plasma current (the Shafranov shift) is accurate to within 15% for aspect ratios greater than two and poloidal betas below 50%, provided the shift does not exceed one tenth of the minor conducting boundary radius. The behavior of the magnetic axis shift as a function of plasma parameters is included.

The Shafranov formulae provide a convenient method for utilizing field measurements to determine the equilibrium behavior of an RFP discharge. Examples illustrating the application of the analytic formulae to estimate the asymmetry factor Λ, poloidal beta and toroidal drift in the Los Alamos ZT-40M RFP experiment are given.

MHD Stability Analysis of ISX-B Discharges*

L. A. Charlton†, B. A. Carreras, J. A. Holmes†, D. K. Lee†,
G. H. Neilson, D. S. Scott and R. M. Wieland†

Oak Ridge National Laboratory
Oak Ridge, TN 37830

We have obtained improved numerical equilibria for MHD stability analysis of ISX-B experiments. The improvements lie in a new parameterization of the current profile which reproduces acceptably the measured data for several classes of discharge. The new profiles allow matching of magnetic probe data, coil currents and Thomson scattering data simultaneously, in contrast with previous profiles which were not totally satisfactory. The results of ideal MHD stability calculations with the ERATO code[1] and with a ballooning code[2] may be summarized: for several values of beta poloidal and for both low toroidal mode number (l=n=5) and the limit n=infinity, the growth rates and ballooning eigenvalues are consistent with the threshold for ideal modes (this can be interpreted as the limit where ideal stability physics begins to take over from the resistive dynamics at lower beta values). The new stability results differ from earlier studies which suggested that ISX-B had definitely surpassed the threshold values of beta.[3]

In contrast with the ideal mode results, the new equilibria exhibit the same resistive stability behavior that was found earlier.[3]

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*Research sponsored by the Office of Fusion Energy, U. S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.
†Computer Sciences at Oak Ridge National Laboratory.
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WAS THIS THE "GREAT SIGN" PROPHECIED AT FATIMA ?

J. Rand McNally, Jr.
103 Norman Lane
Oak Ridge, TN 37830

On July 13, 1917, the Virgin Mary is reported to have prophecied to three shepherd children at Fatima, Portugal: "When you see a night illumined by an unknown light, know that this is the great sign given you by God that He is about to punish the world for its crimes..." Lucia dos Santos, the only living seer of Fatima, believed that if astronomers looked into the unusual aurora of February 25-26, 1938, "they would discover that, in the form in which it appeared, it could not possibly have been an aurora borealis..." Research into this spectacular aurora has revealed that, in addition to the usual features of giant aurorae, a large red spot was observed to fill a volume of about 200 million cubic kilometers. Large aurora may release a total of about 2.5 megatons TNT energy equivalent. The only other giant red spot in the heavens that has been turned up to date is that produced by the upper atmospheric TEAK nuclear explosion (yield possibly 1.4 megatons) of August 1, 1958. This detonation at 77 kilometers over Johnston Island produced a fireball 300 kilometers wide and a red glow occupying a volume of about 400 million cubic kilometers (1). The characteristic red color of these spectacular phenomena was due to the forbidden red lines of oxygen [OI] for which τ = 150 seconds. In both cases large scale electromagnetic pulse (EMP) effects were also observed as a result of significant perturbations of the earth's magnetic field (1,2).

The features and suggestions for some of the physics of these striking plasma phenomena will be presented and suggestions for research will be proposed (2).

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A Multi-Region Fokker Planck Code*

by

M. Baghaii and J. T. Woo
Rensselaer Polytechnic Institute
Troy, New York 12181

ABSTRACT

A multi-region Fokker Planck code is being developed to study heating and relaxation in tandem mirror configuration with distinct regions for MHD anchor, potential plug and thermal barrier to enhance plasma confinement in the center cell. The system is modeled as a series of uniform cells along a flux tube with step changes in magnetic field intensity and potential. These step changes determine the self-consistent velocity space boundaries of each particle distribution in each cell that separates the distribution into locally trapped and various levels of passing particles. The particle distributions in different regions are coupled through interaction with the passing particles. The basic relaxation calculations are carried out by utilizing the FPPAC package[1] which has been incorporated into the code. Self-consistent electrostatic potential in all regions is determined as a multi-variable optimization problem. Estimated running time for problems regarding electronic heat conduction between regions of the tandem mirror, in the presence of external neutral beam and RF heating, for which this code is being developed to address, is in the range of $\leq$ 100 minutes CRAY time.

*This work is supported by DOE contract DE-AC02-81 ER51023.

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Optimal Plasma-β in an MHD-Stable Field Reversed Configuration with Energetic, Large Orbit Ions

L. Sparks and R. N. Sudan
Laboratory of Plasma Studies, Cornell University, Ithaca, NY 14853

J. M. Finn
Naval Research Laboratory, Washington, D.C. 20375

Interchange and ballooning stability in an axisymmetric field reversed configuration is enhanced by the presence of a non-interacting ring of energetic large orbit ions. The equations of motion for large toroidal mode number perturbations can be solved analytically in the vicinity of the vortex point to obtain the ballooning stability condition $F > (1 + |\varepsilon|)/2$, where F is the fraction of the current density carried by the ring ions and ε is the flux surface ellipticity. Modeling the ion ring by an exponential rigid rotor, we use an iterative procedure to obtain numerically optimal values of E_P/E_R, the ratio of the energy of the confined plasma to the ring energy: the ASSYST code solves the Grad-Shafranov equation with specified ring and pressure profiles and computes eigenfunctions and eigenvalues of the Euler-Lagrange equation derived from minimizing the energy integral on each flux surface; the pressure profile is then modified on each flux surface according to the stability results prior to the next iteration. Our numerical results indicate that stability improves as the ring and pressure profiles become more peaked. Stable equilibria are obtained where the total plasma energy is twice the total ring energy. Depending upon the initial choice of ring parameters, the optimal engineering $\beta \equiv 8\pi\langle p\rangle/\langle B_o^2\rangle$ (where B_o is the magnitude of the applied field and brackets indicate a volume average) varies between 1 and 7.

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3C7

ICRF MODE STRUCTURES DUE TO INHOMOGENEITIES*

G. J. Morales, B. D. Fried, and T. Chiueh
Department of Physics
University of California, Los Angeles, CA 90024

The current understanding of short wavelength mode structures of relevance to RF heating in the ion cyclotron range of frequencies (ICRF) has been obtained primarily by WKB analysis of local dispersion relations. The present studies are aimed at illustrating some new features which are intrinsically related to plasma inhomogeneities (i.e., density, magnetic field). Here we report on 3 related topics of importance to present and future ICRF experiments: 1) Generation of new quasi-electrostatic modes from pre-existing short wavelength, low frequency, density inhomogeneities; 2) Excitation of finite amplitude cold electrostatic oscillations at the gyroresonant layer ($\omega = \Omega_i$); and 3) Effect of ion ponderomotive drift on low frequency drift wave turbulence.

In topic 1) a formulation is used that explicitly separates magnetic vector potential and electrostatic contributions to describe the modes recently identified by R. J. Taylor. To study topic 2) a differential equation that retains the inhomogeneity of the magnetic field in the cold plasma limit is solved. This result permits the calculation of the Green's function necessary for finding the coupling to external sources. In topic 3) the ion ponderomotive drift is incorporated into the Hasegawa-Mima equation and a suitable singular stability analysis is performed.

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Heliac Stability*

D. A. Monticello and R. L. Dewar
Princeton Plasma Physics Laboratory, Princeton, N.J. 08544

Heliac, a stellarator with a helical magnetic axis winding around a central, current-carrying conductor, has been shown to have a deep magnetic well for some configurations, and hence good stability at low values of β.[1] We report here results of our investigation of the β limits of these devices. In order to analyze the straight heliac, we have generalized our axisymmetric flux coordinate equilibrium code to treat the case of helical symmetry [i.e. $\vec{B} = \vec{B}(r,u)$, $u = \ell\phi - hz$]. the stability to ideal and resistive interchange modes and to ideal ballooning modes is evaluated using a code written in general (Ψ, θ, δ) flux coordinates. Conversion of the PEST 2 finite element code to these coodinates has also been accomplished and we will report results from this code. Results thus far indicate that if the vacuum magnetic field configuration for heliac is V" stable the beta limits are very high (in excess of 15% average β and 100% β on axis) for stability against high n ballooning, ideal and resistive interchange. This result is for heliac with zero net current through each flux surface. Heliacs with other current configurations have been found to be less stable, including those with no net current. Broad pressure profiles have also been found to be favorable to ballooning, as in the toroidal case. Parameter studies are underway to determine the effects of aspect ratio, h and outer flux surface shape on stability.

*This work was supported by United States Department of Energy Contract No. DE-AC02-76-CHO3073.

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Oral

WAVE PROPAGATION IN BUMPY TORUS

K. W. Whang*, T. Shoji
Institute of Plasma Physics, Nagoya University,
Nagoya 464, Japan

The slow Alfven wave ($\omega \sim \Omega_i$) propagation in bumpy tori is investigated. The partial reflection of the principal mode as well as the reactive excitation of the higher wavenumbers, and secondary modes due to the bumpy boundary are found to modify the dispersion relation with respect to that of a straight cylinder in such a way as to inhibit a free propagation. When the principal mode becomes a standing wave, a series of frequency stop band occur where the wave cannot propagate more than few cavities. The magnitude of the frequency downshifts, the locations and band gap widths as functions of frequency are computed. The relevance of these properties to ICRH in a bumpy torus will be discussed.

*On leave from Department of Physics, University of California, Los Angeles, California 90024, U.S.A.

Effects of Impurity Radiation on Proto S-1C Spheromak*

Y. C. Sun, S. C. Jardin, R. A. Hulse and M. Yamada

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

The Proto S-1C spheromak peak temperature predicted by a previously reported simulation code[1,2] is much higher than those experimentally measured.[3,4] To improve the impurity treatment, we implement the non-coronal equilibrium model in our MHD code. A set of ionization rate equations is used to compute the ionization state distributions and the resultant radiation power levels. These radiation losses are then coupled to the MHD equations. Using Proto S-1C spheromak parameters and carbon and oxygen as impurities, time evolution of temperature, magnetic surfaces and other plasma properties are computed. Comparison with experimental measurement is made.

*This work supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

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Poster Session

3C11

FINITE TEMPERATURE EFFECTS IN FREE-ELECTRON-LASER AMPLIFIERS*

L. Ibanez and S. Johnston

Plasma Physics Laboratory
Columbia University
New York, New York 10027

The effect of energy spread on the gain of a dense free-electron-laser amplifier is analyzed. The formalism is valid to all orders in the pump, includes collective effects and a guide magnetic field, and allows for the use of an arbitrary distribution function. The dispersion relation is solved numerically for several distribution functions. Besides a broadening of the spectrum and a decrease in gain, a lowering of the central emission frequency with energy spread is observed. Due to strong Landau damping of the mediating plasma wave for realistic beam quality, the question arises whether the constructive spatial interference of the modes may represent an alternative means of amplification. To this end, the differential equations governing the fields are solved numerically by Laplace transformation. This approach allows for an arbitrary initial distribution function at the entrance of the interaction region as well as the base equilibrium distribution.

The presence of the guide magnetic field introduces two different types of stable orbits[1]. For one class of orbits, the existence of a threshold energy leads to branch points in wave-vector space. The associated branch cuts yield additional contributions to the fields upon inversion of the Laplace transform.

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ENERGETIC ELECTRON TAIL FORMATION BY MULTIPLE FREQUENCY ELECTRON CYCLOTRON RESONANCE HEATING

T. K. Samec and B. I. Hauss, TRW

ABSTRACT

Experiments on Elmo ring formation in the TRW SM-1 axisymmetric mirror have demonstrated that multiple frequency electron cyclotron heating (MFECH) can result in dramatic increases in ring stored energy.[1] The optimum frequency separation is remarkably small ($\Delta f/f \gtrsim 0.5\%$). These observations have spurred a flurry of theoretical investigations of the fundamental processes of ECRH.[2,3] These detailed analyses have been focused on very restricted regions of velocity space in which the super-adiabatic behavior resulting from single frequency heating is most easily affected by MFECH. Monte-Carlo calculations show dependences of the heating rates on frequency separation and sideband power which are strongly reminiscent of experimentally observed results. The detailed predictions of these calculations however can not be verified experimentally. Reproducing the experimental observations of increased ring stored energy are also far beyond the reach of existing Monte-Carlo codes.

In order to bridge this gap we have begun a Monte-Carlo analysis of the formation of the warm electron population (energy $\lesssim$ 500 eV). Particular attention is being paid to measurements of the flux of electrons which are run away from the quasi-thermal bulk since these electrons contribute directly to the formation of the Elmo ring. We have observed a strong dependence of this flux on the microwave heating spectrum. These new results, along with a summary of previous results[2] will be presented.

This work was supported by the Department of Energy (DEAC 63-80 ET 51017) and the TRW IR&D program.

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A Kinetic Wave Expansion for the Plasma Fields Generated by an External Coil in a Slab Geometry

B.D. McVey
Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, Massachusetts USA

Wave propagation in a warm magnetoplasma be can described by*formulating an equivalent dielectric tensor which replaces the relative permitivity in Maxwell's equations. In its usual form, a plane wave ($exp(ik_x x + ik_z z - i\omega t)$) is assumed for the EM perturbation, and the determinant of the dielectric tensor defines the dispersion relation for the various plasma modes. In many low frequency RF heating applications, the frequency (ω) and the parallel wave number (k_z) can be assumed to be fixed; and the dispersion relation can be cast into the form of a complex polynominal in (k_x^2) of infinite order defining a likewise infinite set of plasma waves. For an external source such as an RF antenna, it is of interest to determine the excitation level of each of the plasma waves at the plasma-vacuum interface. A set of boundary conditions for this problem is derived, and it is found that the boundary conditions result in a convergent plasma wave expansion of a character similar to a Fourier series expansion. Numerical examples are presented in which the complete hot dispersion relation is solved and up to thirty waves are retained in the summation.

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3C14

CAN TOKOMAKS SUCCEED TO REACH FUSION DOMAIN

Michel COTSAFTIS

Tokomaks are now suffering from a levelling off of their performances, due to : 1- disruptions, and 2- β-limitations . It is shown that both phenomena have a common origin in the fact that Tokomak structure has a "weak" point at the X-point of the mode (m=1,n=1), and any move weakening again this point ends up with discharge destruction . Two ways are possible . From the outside, by the excitation of the mode (m=2,n=1) which toroidally couples to the mode (m=1,n=1) – for weak enough density $n_e \lesssim 0.7 \div 0.9\ 10^{14}/cm^3$ – , and from the inside, by depositing too much power inside the surface q=1 . In both cases, the mode (m=1,n=1) is excited at a level for which the neighbouring higher order modes are themselves excited at a point where they ergodically interact . This destroys the X-point and opens the central core out of which the energy flows out without replacement, like in case 1 with ohmic heating alone, with replacement, like in case 2, making this second situation less dramatic . Note that for higher density disruptions, the neighbouring islands in between m=1 and m=2 are overlapping first before toroidal coupling between these two modes will occur . Then the central core is isolated in a large ergodic region and becomes kink unstable .

The theoretical analysis of these phenomena, which have been carefully observed in many different experiments, has been set down on the only base of the existence of branchings to islands structure, of Drift-Tearing type, in a basic Tokomak one . Various properties of these islands are discussed, and especially the fact that they can exist as oscillatory limit cycle, the amplitude of which has been evaluated . Stability criteria, corresponding to the nonlinear instability of the mode (m=2,n=1) in case 1, and to the birth of local ergodicity around the mode (m=1,n=1) in case 2, have been given . Various situations are considered with or without control of the mode (m=2,n=1) and the corresponding discharges are discussed . It is concluded that the high density low q case is the worst for steady operation safe from difficulties 1 and 2 . Instead, it is alternatively proposed to start as a Tokomak and then slowly change to a Stellarator without the surfaces q=1, q=2 inside the plasma volume, in order to avoid their deleterious effects onto the discharges .

Optimization of Steady-State Beam-Driven Tokamak Reactors*

D. R. Mikkelsen and C. E. Singer
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

Abstract

Recent developments in neutral beam technology prompt us to reconsider the prospects for steady-state tokamak reactors. Analytic models are developed for the physics of beam-driven currents and reactor power balance, as well as for the reactor and beam system economics. These models are used to find the plasma density and temperatures which minimize the cost per unit of net electrical output from a reactor. For an INTOR-sized reactor which has $\langle\beta_{thermal}\rangle$ = 7%, we find that the optimum plasma is characterized by $\langle n_e\rangle \sim 1.7 \times 10^{14}$, $\langle T_i\rangle_n \sim$ 17 keV, $\langle T_e\rangle_n \sim$ 14 keV, and the optimum beam is D^o at ~ 2 MeV. In such a reactor $\langle\beta_\alpha\rangle \sim$ 1.2% and $\langle\beta_{beam}\rangle \sim$ 0.5%. We encourage further theoretical work on Alfven wave instabilities driven by the anisotropic beam-ion distribution and on the influence of the large fast ion pressures on MHD stability.

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Oral Session

Full MHD Equations vs Reduced MHD Equations: A Comparison of Results*

J. A. Holmes†, B. A. Carreras, H. R. Hicks†,
V. E. Lynch†, B. F. Masden†, and T. C. Hender

Oak Ridge National Laboratory
Oak Ridge, TN 37830

We solve a full set of nonlinear resistive MHD equations in 3 dimensional cylindrical geometry using a new initial value code, CYL. This code, which has both compressible and incompressible options, includes finite aspect ratio effects by limiting the length of the cylinder to $L=2\pi a/\varepsilon$ in the axial direction. With periodic boundary conditions in L, CYL time advances the equations using a mixed radial finite difference, axial and angular Fourier series representation similar to that employed in the reduced equation RSF code.[1] The time advancement scheme, which can be chosen to be either explicit or partially implicit, is first order accurate in time δt and second order in radius δr.

Comparison between CYL and RSF for a variety of cases indicates excellent agreement in the limit of large aspect ratio, and only minor differences in results for inverse aspect ratio $\varepsilon \lesssim 0.3$. Even for $\varepsilon = 0.5$ the results of the two codes are surprisingly similar. We shall present results of linear growth rates, saturated island widths, and detailed time evolutions. In particular, the nonlinear destabilization of the (m=3; n=2) mode due to the coupling of modes having different helicity, which has been previously calculated with RSF and which is believed to be the cause of some major tokamak disruptions,[2] is also observed with the CYL code. These results indicate that the large aspect ratio ordering used to derive the reduced MHD equations[3] employed in RSF is a reasonable approximation even at typical tokamak aspect ratios ($\varepsilon \approx .25$).

The CYL code is also suitable for calculating the reversed field pinch configuration, and initial results of these calculations will be presented.

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†Computer Sciences at Oak Ridge National Laboratory.

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VELOCITY-SHELL INSTABILITIES*

Robert W. Huff, J. M. Dawson, V. K. Decyk, I. Jechart, T. Katsouleas,
C. F. Kennel, J. N. Leboeuf, R. M. Martinez, and D. Sentman
University of California, Los Angeles, CA 90024

Instabilities of spherical shell distributions in velocity space, plus a cold Maxwellian background, were simulated with a 2.5D electrostatic particle code, with a magnetic field either parallel or perpendicular to the gridplane. Such distributions were long thought to be stable. The observed instabilities are in agreement with the zeros of the dielectric function, as found from the resonant approximation (parallel fields) or by computation with a root-solver code (perpendicular fields). Saturation of the instabilities is due to cyclotron resonance (parallel fields) or particle trapping (perpendicular fields). This trapping mechanism couples to acceleration of the particles parallel to the wave front via the $V_{phase} \times B$ force (dynamo mechanism). It is capable of accelerating particles to much greater velocities than the phase velocity of the trapping wave, within a few cyclotron periods. Hence, a small number of particles very effectively damp the wave.

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CENTRAL CELL AND BARRIER PARAMETERS IN AN AXISYMMETRIC TANDEM

R. A. Jong

Lawrence Livermore National Laboratory, University of California

Livermore, California 94550

ABSTRACT

We describe a procedure for calculating density and potential profiles in the central cell and barrier regions of a tandem mirror with an inside axisymmetric barrier. The sloshing ion and pump beams and microwave power requirements to produce the potential and density profiles in the barrier and central cell are calculated.

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3C19

MEAN FIELD APPROACH TO RENORMALIZED PERTURBATION THEORY

R. V. Jensen

Yale University, Applied Physics,
P.O.Box 2159, New Haven CT 06520

C. R. Oberman

Princeton Plasma Physics Laboratory,
Princeton NJ 08540

Using the functional integral representation of nonlinear dynamics[1], we present a new, systematic method for developing renormalized perturbation theories. Essentially, we approximate the exact nonlinear equations of motion by linear Langevin equations with renormalized "viscosities" and sources of turbulent "noise". This procedure reduces problems in nonlinear statistical dynamics to Brownian motion.

Our method is physically appealing because turbulent behavior nonlinear dynamical systems is often characterized by effective "viscosity" and "noise". We provide explicit results for the approximations corresponding to the Direct Interaction Approximation and the Lagrangian History Direct Interaction Approximation.

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SIMULATION OF ELECTRON TEMPERATURE PROFILES FOR DIFFERENT VALUES OF q (*)

N. N. Sharky

Massachusetts Institute of Technology, Cambridge, MA 02139

Simulation of tokamak discharges with a 1-D transport code often yields electron temperature profiles whose shape is nearly independent of the toroidal magnetic field B_T and the plasma current I_p. The experimental $T_e(r)$ profiles, however, vary strongly with these two parameters and, in particular, with $q(a)/q(0)$ where $q(r)$ is the safety factor. Since the computed loop voltage V and electron energy confinement time τ_{Ee} depend on the shape of the $T_e(r)$ profile, it is important to reproduce the correct variation of the $T_e(r)$ profile when analyzing the scalings for V and τ_{Ee} with I_p and B_T.

The reason for the above-mentioned difficulty can be understood from the analysis of Refs. 1 and 2, where a class of electron thermal diffusion coefficients of the form $\chi_e \propto T_e^{\alpha} q^{\beta}/n_e$ is considered. In particular, it is shown that the computed $T_e(r)$ profile, obtained by balancing the Ohmic heating power and the electron conduction loss, has a <u>fixed</u> shape for a given transport model (i.e., the value of $q(a)/q(0)$ depends only on α and β).

When atomic processes are appropriately included in the model, significant changes in the $T_e(r)$ profile can occur, since cooling of the plasma edge must be accompanied by a steepening of the $T_e(r)$ profile (for given I_p). This effect has, in fact, been demonstrated for particular discharges by including impurities[3] and neutrals[4] in the transport model.

Our purpose here is to carry out a systematic analysis of these edge effects on the $T_e(r)$ profile for different values of B_T and I_p. Using measured data (whenever available) on the radiated power as a function of I_p and B_T, we shall try to determine, with the help of a 1-D code, whether impurity and neutral effects can account for the observed variation of the $T_e(r)$ profile with q in various experiments.

In addition, analytical expressions for $T_e(r)$ and V, that take into account approximately these edge losses, have been derived. The atomic processes are assumed to be prevalent at $r \geqslant r_2$. Then taking the exponent $\beta = -1$, and following the method of Ref. 1, the energy balance equation is integrated inwards from r_2 to r. The solution (for $\alpha > -1$) is $T_e(r) = T_e(r_2) \times [\, 1 + K \times (1 - r^2/r_2^2)\,]^{\gamma}$, where $\gamma = 1/(1+\alpha)$ and K depends on $T_e(r_2)$ and other parameters. The impurity and neutral losses affect the $T_e(r)$ profile in the inner region (and hence the loop voltage) by decreasing $T_e(r_2)$ and increasing K. For $\alpha = -1$, although the solution takes a different form, the edge losses have a similar effect on the $T_e(r)$ profile.

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Saturation of Tilting of Particle Rings*: R. V. Lovelace and C. B. Ruchti, Cornell University

A saturation mechanism is proposed for the unstable tilting of large orbit particle rings. The condition for the linear stability of a large orbit ion or electron ring against tilting can be expressed as $\omega_z<\Omega$, where ω_z is the axial betatron frequency and $\Omega=v_\theta/R$ is the circulation frequency.[1] In a dense plasma the tilting motion is expected to be slow with the magnetic force on the ring particles dominant.[1] Thus the canonical angular momentum (P_θ) of a ring particle will change in the process of tilting, but its Hamiltonian (H) will remain a constant. We have calculated a sequence of self-consistent equilibria by the methods of (2) each with a single $H=\langle H\rangle$ with and $P_\theta=\langle P_\theta\rangle$ for a range of values of $\langle P_\theta\rangle$. Decreasing $\langle P_\theta\rangle$ with $\langle H\rangle$=const. leads in general to longer axial length ring equilibria with smaller values of ω_z/Ω and smaller values of $\delta=|B_s(0)/B_{ext}|$ (see Fig.). Linear stability of the tilting is found to occur for rings which are still strongly field-reversing, $\delta\gtrsim1.5$.

*Work supported by DOE contract DE-AS02-76ET53017.

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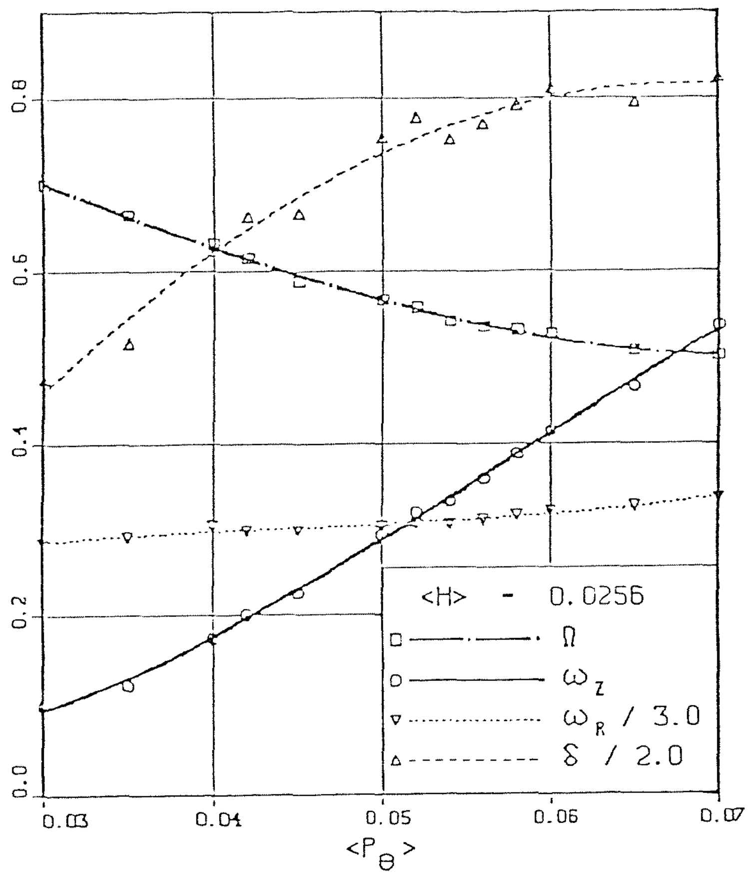

An Fokker-Planck Kinetic Approach for Collisional Particle Transport in a Field-Reversed Theta Pinch

M.-Y. Hsiao and G. H. Miley
Fusion Studies Laboratory, University of Illinois
214 NEL, 103 S. Goodwin Avenue
Urbana, Illinois 61801

As in the case of the loss cone in velocity space for a simple mirror, an unconfined region in (H, P_θ) space, or equivalently in velocity space, is expected to have significant effects on plasma behavior in field-reversed theta pinches (FRTPs). In this paper, we adopt a Fokker-Planck kinetic approach to study the effect of this loss region on collisional particle transport in FRTPs, especially in steady-state operation.

Although the original form of particle confinement criterion is given in (E,P_θ) space,[1] for the present application it is reformulated in ($\underset{\sim}{r},\underset{\sim}{v}$) phase space. The approach used in our previous work[2] which invokes transformations to obtain separation of variables is extended here to 6-dimensional phase space ($r,\theta,z,v_r,v_\theta,v_z$). The full Fokker-Planck kinetic equation, i.e., Boltzmann equation with Fokker-Planck collisional term, subject to the confinement criterion, is solved approximately for the particle distribution function.

In present calculations, static $\underset{\sim}{B}$ and vanishing $\underset{\sim}{E}$ are assumed, and only one species is considered. Procedures are as follows: (1) Shift origin of (v_r,v_θ,v_z) coordinates from (o,o,o) to ($o,-qB_0r/mc,0$) and change $\underset{\sim}{v}$ to $\underset{\sim}{v}/(q^2B_0(B_0r^2/2\psi)/m^2c^2)^{1/2}$. (2) Use a model velocity distribution (modified Rigid Rotor) which satisfies the boundary condition in velocity space set by the particle confinement criterion to evaluate the velocity integrations of Rosenbluth potentials. (Later, the assumed model velocity distribution is tested for validity) (3) Use separation of variables to divide the kinetic equation into a set of simpler equations. (4) Solve the separated equations and obtain an analytic expression for the particle distribution function. Resulting density profiles and velocity distributions follow trends similar to the 1-D case of Ref.2.

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Heating of Tokamaks via Alfven Wave Excitation

C. E. Kieras and J. A. Tataronis
The University of Wisconsin
Madison, WI 53706

The possibility of heating a magnetically confined plasma via resonant excitation of waves belonging to the shear Alfven continuum of ideal MHD theory depends crucially on whether or not these modes are characterized by non-square-integrable spatial singularities. For a compressible plasma in a cylindrical screw pinch, the radial structure of the perturbed velocity is known to exhibit a logarithmic singularity, $v_r \sim \ln (r - r_0)$, at the resonant surface, r_0, where the driving frequency, ω_0, is equal to t local Alfven frequency, $\omega_A (r_0)$. However, for an incompressible plasma in a cylindrical screw pinch, the radial behavior is characterized by an essential singularity, $v_r \sim (r - r_0)^{\nu}$, where ν is imaginary. In this study, the equations which determine the radial structure of a wave belonging to the shear Alfven continuum of an axisymmetric tokamak are derived, analyzed, and compared with earlier treatments [1,2,3]. The system of equations simplifies considerably when the limit of zero pressure is taken. In this limit, it is shown explicitly that the perturbed velocity exhibits a logarithmic singularity about the resonant surface. The results of this analysis are used to predict the energy absorption rate due to Alfven wave excitation in tokamak geometry. The theory is applied to the Tokapole II experiment at the University of Wisconsin.

The work is supported by National Science Foundation Contract No. ECS-8110038.

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Oral Presentation requested

1982 Sherwood Meeting
Sante Fe, New Mexico
April 25-28, 1982

PARAMETRIC PHENOMENA AT ELECTRON CYCLOTRON RESONANCE HEATING OF TOKAMAK PLASMAS*

V. Stefan and A. Bers**
Massachusetts Institute of Technology
Plasma Fusion Center
Cambridge, Massachusetts 02139, U.S.A.

The aim of this paper is a theoretical study of parametric processes near the electron cyclotron resonance region in tokamak plasmas. Parametric dispersion relations, including finite wave length of the driver pump and principal and second harmonic parametric excitations are given. We study the problem of primary and secondary decays including their temporal and spatial growth rates. In the nonlinear phase of development of the excited waves we invoke a cascading saturation mechanism for both convective and absolute [1] parametric instabilities. Anomalous absorption lengths and anomalous collision frequencies are evaluated for a variety of parametric excitations. We compare the effectiveness of nonlinear absorptions in the case of absolute and convective instabilities. Excitation of electron Bernstein modes [2] coupled with lower hybrid waves seems to be the most promising decay channel in the ECF domain. Finally we discuss the accessibility of the X-mode in strongly magnetized plasmas, and give a comparison between linear and nonlinear absorption processes.

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* Work supported by DOE Contract No. DE-AC02-78ET-51013.

**Visiting Scientist from "Boris Kidric" Institute of Nuclear Sciences, Belgrad, Yugoslavia.

3C25

Scattering of Lower Hybrid Waves: Solutions of the Radiative Transfer Equations*

P. A. Andrews and F. W. Perkins
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

An integro-differential radiative transfer (wave-kinetic) equation governs the scattering of lower hybrid waves by drift wave density fluctuations. We consider a model geometry where the drift wave turbulence is contained within a slab of thickness ℓ. Solutions to the radiative transfer equation are presented for two limiting cases: First, the driftwave wavelengths are much larger than the lower hybrid wave wavelength, and, secondly, where the converse is true. In the first case, the individual scattering angles are small and the radiative transfer equation simplifies to a differential equation. In the second case, a simple form of the differential scattering cross-section is obtained. For both cases, we show that the intensity of the flux transmitted through the turbulent slab scales inversely with the slab thickness and that the angular spectrum of the emerging radiation intensity $dI/d\theta$ has a cosine dependence: $dI/d\theta = (\text{const.}) \cos\theta$. The constant of proportionality will be presented in terms of driftwave wavelength, the magnitude of driftwave density fluctuations, slab thickness, etc.

*This work supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

Poster Session

LIMIT CYCLES IN ELECTRON CYCLOTRON HEATING

G.E. Guest
AMPC Inc.
Encinitas, CA 92024

ABSTRACT

The energy and pitch angle of electrons heated by electron cyclotron heating (ECH) in axisymmetric magnetic mirrors are predicted, under some conditions, to undergo slow oscillation about stable (elliptic) fixed points [1]. This phenomenon can limit the maximum energy an electron gains and also prevent its loss from the magnetic mirror unless stochastic heating is brought about by some additional mechanism [2]. The possibility of selectively enducing stochastic heating of these collisionless electrons as a way of enhancing ELMO ring formation and control [3] has motivated a further study of one particular type of ECH limit cycle. Here we obtain analytic conditions for the null-heating surfaces discussed by Samec et al [2] using a convenient and possibly novel form for the electron gyrophase relative to a coherent ECH wave. With these analytic conditions, one can deduce some of the more important properties of null-heating surfaces for a wide range of ECH situations prior to undertaking a detailed KAM mapping study of the most promising applications.

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SOLITON KINETIC EFFECTS

Philip J. Morrison and James D. Meiss
University of Texas at Austin
Department of Physics and
Institute for Fusion Studies

The linear theory of drift waves for tokamaks in the slab geometry approximation involves a source due to electron kinetic effects and a sink due to ion Landau damping. Among the nonlinear theories proposed for the explanation of the observed broad spectrum is that of soliton formation.[1] These solitary waves are obtained from fluid equations and hence do not include the influx and outflux of wave energy. As a stepping stone to the more appropriate two-dimensional drift wave equations, we discuss two kinetic calculations associated with the ion-acoustic soliton. First, we present an ion kinetic ordering which yields the usual K dV equation when moments are taken, but with finite ion temperature corrections. These kinetic equations contain ion Landau damping. Second, we present an O'Neil[2] type frozen wave calculation for electron trapping in an ion acoustic soliton. This calculation differs from a previous calculation[3] involving ion acoustic solitons and electron Landau damping, in that the usual three time scale separation argument is made: $\omega \gg \omega_B \gg \gamma$. The trapping effects included in this ordering become important at the modest amplitude $e\phi/T_e \gtrsim (m_e/m_i)^2$ which is easily exceeded by an experiment.

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Equilibrium β Limit for the Heliac Configuration

F. Bauer, O. Betancourt

New York University, New York, N. Y. 10012

and

T. K. Chu

Plasma Physics Laboratory, Princeton University, New Jersey

We examine finite β effects on current free Heliac equilibria by studying the shift of the magnetic axis relative to the separatrix (last closed flux surface). An equilibrium β limit can be defined by a shift equal to half the plasma radius.

We describe the shape of the separatrix by an equation obtained from a line tracing code. This is used as input to the NYU 3-D equilibrium code, which is then used to compute finite β equilibria.

Results for the shift as a function of β, as well as other quantities like rotational transform, well depth, etc. will be shown.

Work supported by U. S. Department of Energy Contracts Nos. DE-AC02-76-ER03077 and DE-AC02-76-CHO-3073.

Poster Session. Please schedule adjacent to paper "Numerical Studies of Zero-Net Current Torsatrons."

ABSTRACT

"An Analysis of Taylor's Theory
of Toroidal Plasma Relaxation"

by

Vance Faber, Andrew B. White, Jr., G. Milton Wing

The Taylor theory of toroidal plasma relaxation is considered as a nonlinear eigenvalue problem. The analysis is rigorous and applies to quite general toroidal cross sections. Emphasis is placed on the symmetric state case, where the existence of field reversal and flux free states is demonstrated. Certain anomalies are revealed by the mathematical treatment and their significance is studied. Existence of a solution to the Taylor problem in the symmetric state is proved and the location of the eigenvalue of this solution state relative to other states is examined. The question of the existence of helical states is not resolved, but it is shown that in many respects any helical states behave like the anomalous cases in the symmetric problem and hence do not significantly affect the theory.

PAC Numbers 52.55.Gb
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3C30

SATURATED TEARING MODES IN TOROIDAL GEOMETRY

Glenn Bateman and R. N. Morris
School of Nuclear Engineering and Health Physics
Georgia Institute of Technology
Atlanta, Georgia 30332

A formalism has been developed for the determination of saturated tearing mode amplitudes in axisymmetric toroidal geometry with no assumptions on the cross-sectional shape, aspect ratio, or plasma pressure (beta). The formalism entails an expansion of the 3D scalar-pressure plasma equilibrium equations to first order in the perturbed magnetic field--effectively an expansion in the width of the magnetic islands compared to the minor radius of the plasma. The problem encountered is that the perturbed current is best expressed in terms of the covariant components of the perturbed magnetic field, while $\nabla \cdot B = 0$ is best expressed in the contravariant components. If flux coordinates are used and a Fourier decomposition taken in the angles, the relations between covariant and contravariant components produce Fourier convolutions under the derivatives and an intractable system of equations. The key to our formalism is to use the mix of contravariant and covariant components (B^{1V}, B^1_θ, B^1_ζ, p^1) as the primary variables. A system of ordinary differential equations can then be derived for the helical harmonics (B^{1V}_{mn}, $B^1_{\theta mn}$) as a function of V in Hamada coordinates (V, θ, ζ). Fourier convolutions are needed only to evaluate the driving terms of these ordinary differential equations. The ODE's are formally singular at mode rational surfaces, but the presence of the magnetic islands will locally flatten the pressure and parallel resistivity profiles remove the singularity. The widths of the magnetic islands then serve effectively as eigenvalues for the solution of these ODE's as two-point boundary value problems. An iterative alogorithm can then be used to simultaneously adjust the widths of all the islands being considered, determine their effect on the axisymmetric profiles, solve for the adjusted axisymmetric equilibrium, solve the ODE's for the helical harmonics, and determine the new widths of the magnetic islands to close the cycle.

This work was sponsored by the U. S. Department of Energy, Division of Applied Plasma Physics.

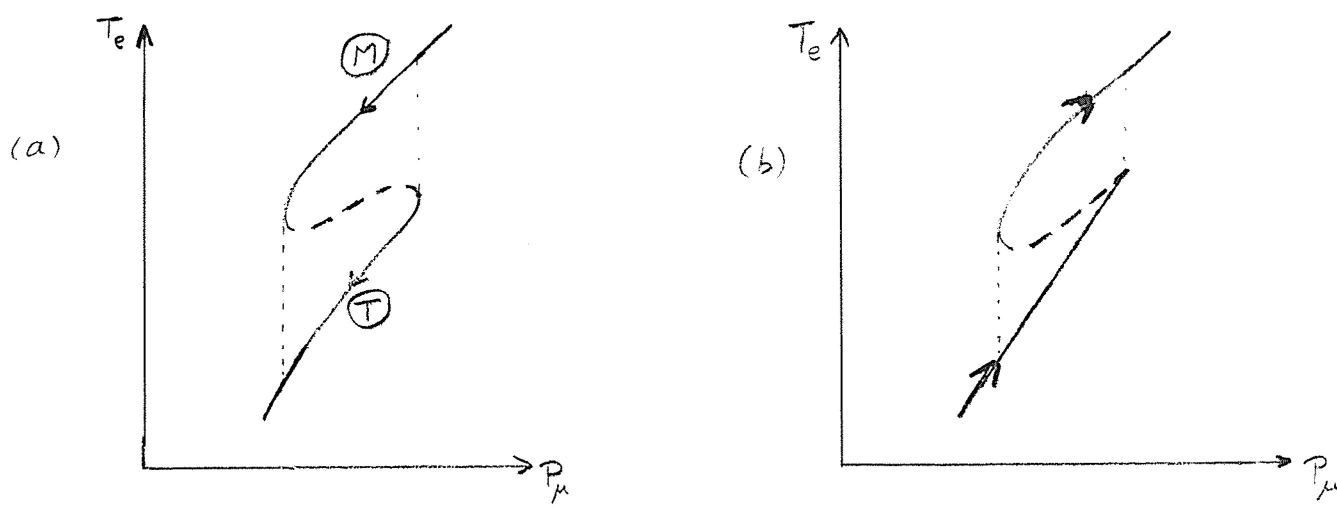
3C31

CATASTROPHES IN EBT - NEOCLASSICAL ELECTRONS WITH ICRH

Alkesh Punjabi, George Vahala (William & Mary)

and Edward G. Harris (University of Tennessee)

We extend our previous treatment[1] of catastrophes in EBT by including the effects of ICRH in the simple neoclassical non-resonant point model of Hedrick et. al. Since the ions (in current experiments) are believed to follow some form of resonant transport, we do not specify their transport coefficient and so obtain closure by specifying ambipolarity and neoclassical electron transport with ambipolar potential ϕ as an external parameter. E_r is taken to be radially in. The fold structure in the behavior surfaces and the T-M transition are studied as the external parameters are changed. Typical structure as we increase ICRH to pass form (a) $T_i < T_e$, to (b) $T_i > T_e$ is shown below



P_μ = microwave power (for electron ring formation)
T_i, T_e $\equiv$ ion, electron temperature
The long broken lines $\equiv$ unstable sheet, dotted lines $\equiv$ delay convention jumps [arrows show direction of T_i/T_e increasing]. The point model is also solved as an initial value problem so as to distinguish between the Delay and Maxwell conventions for the onset of the catastrophe jumps.

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3C32

Numerical Studies of Zero-Net Current Torsatrons

O. Betancourt, F. Bauer

New York University, New York, N. Y. 10012

A fully three dimensional ideal MHD code has been used to find torsatron configurations with finite critical values of the plasma parameter β. The equilibrium and stability properties are found to depend on the Fourier components of the separatrix.

Equilibrium and stability limits will be discussed for several configurations. In addition, winding laws for the helical coils will be described, as well as the relationship between parameters and the resulting shape of the separatrix which determines the β limits.

Work supported by U. S. Department of Energy Contract No. DE-AC02-76-ER03077.

Poster Session. Please schedule adjacent to paper "Equilibrium β Limit for the Heliac Configuration."

Electron Bounce Resonance Heating in a Mirror Confined Plasma*

J.D. Callen and K.C. Shaing

Nuclear Engineering Department, University of Wisconsin
Madison, Wisconsin 53706

For a mirror confined plasma electrons are usually confined in the electrostatic potential well with a characteristic bounce frequency ω_b. If there is a wave with frequency $\omega = \omega_b$ in the system, there can be a resonant interaction between the wave and electrons. The basic resonant mechanism is collionless (bounce) Landau damping. The power transfer from the wave to electrons is calculated from a quasilinear theory. Since the electron bounce frequency ω_b is usually of the order of the ion gyrofrequency Ω_i in a mirror machine, significant electron bounce resonance heating can occur from waves in the plasma in the ion cyclotron frequency range. The theory is offered as a possible explanation for the temperature difference between plug and central cell electrons in the TMX[1] experiment. It is also shown that electron bounce resonance heating may be able to deliver significant electron heating power in the reactor regime.

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*This work was supported by the U.S.Department of Energy contract No. DE-AC02-80ER53104.

FILAMENTATION IN HIGH-β PLASMAS AND SUPERCONDUCTIVITY

George Vahala (W.& M.) and Linda Vahala (O.D.U.)

One of the most striking differences usually pointed out between superconductors ($\sigma = \infty$ + quantum mechanics) and perfect conductors ($\sigma = \infty$ + classical mechanics) is the expulsion of flux from superconductors — Meissner effect — and 'frozen-in' field lines in perfect conductors. The London equations, which explain flux expulsion, can be justified by microscopic BCS theory. Recently, Edwards[1], for the first time, has shown that the London equations can be derived classically so that high β plasmas could also exhibit type II superconductivity properties.

A striking example is the radial striation structure always seen experimentally in the current sheath (c.s.) of a plasma focus during the 'run-down' phase, although application can also be made to both Z-pinches, θ-pinches and magnetic flux ropes in the Venus ionosphere[1]. Type II Superconductors: For suff. small $\vec{H}_{ext} \Rightarrow$ field line expulsion. $\vec{H}_{ext}$ increases $\Rightarrow$ flux penetration via regular array of quantized flux tubes with a vortex of supercurrent surrounding each flux tube. Plasma Focus[2]: c.s. is a "2D film" with a large H_θ behind it. 2D film $\Rightarrow$ flux penetration via pairs of oppositely directed vortices. Steady state run down phase of c.s. $\Rightarrow$ these vortices are "pinned" on the electrode surfaces, i.e. the vortices are directed radially in the c.s. As H_θ increases the vortex pairs collapse releasing energy and destroying the "superconductivity" state so that the striations disappear and the c.s. becomes uniform. The pinning of the vortices on the electrodes allows current to flow through these vortex cores which together with the shielding vortex supercurrents gives rise to the typical helical field line ("flux rope") structure in these filaments[2].

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3C35

IMPURITY EFFECTS IN A SMALL RFP REACTOR

R. N. Byrne and D. Dobrott

The ohmic power requirements necessary to maintain steady state increases with impurity level in a Reversed Field Pinch reactor and can potentially degrade the reactor plasma Q (= power out/power in). These requirements are more critical for an RFP than for a tokamak because of the presence of large poloidal current densities near the edge of the plasma where the plasma resistivity is high.

This point is illustrated by representative power balance calculations for a small deuterium-tritium fuelled RFP reactor using the DDRFP reactor code[1]. In addition to classical and alcator transport, these calculations included enhanced Christiansen-Roberts transport[2] where the plasma was interchange unstable. The [illegible]ting flat density and temperature profiles are thus MHD stable to interchange. A sequence reactor burn of simulations have been performed, while the impurity was varied from oxygen to tungsten. The level of impurity was adjusted to maintain approximately constant average temperature. The level of impurity required to maintain this quasi-steady state decreases with increasing impurity Z, i.e., Zeff decreased. The resulting Q varied from 2 for oxygen to 10 for tungsten.

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Modelling of Lower Hybrid Current Generation*

E. J. Valeo, J. M. Ogden, and F. W. Perkins
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

We have developed a computer code which models the following aspects of lower-hybrid current generation and heating: quasilinear and collisional diffusion and pitch angle scattering of electrons, self-consistent poloidal flux diffusion including nonlinear conductivity modifications, and toroidal effects on ray propagation. Particular attention is paid to the crucial role of the high wavenumber components of the wave power spectrum which establish the size of the wave electron interaction. Applications of the code to interpretation of experimental data will be presented.

*This work supported by United States Department of Energy Contract No. DE-AC02-76-CH03073.

Poster Session

3C37

MODELS FOR POLOIDAL DIVERTORS AND PUMP LIMITERS

D. Post, D. Heifetz, and M. Petravic*

Princeton University, Plasma Physics Laboratory

Princeton, NJ 08544

ABSTRACT

Pump limiters and poloidal divertors have been proposed for particle control and impurity control in large tokamaks. We have modeled the pumping characteristics and plasma parameters (density, temperature) to be expected for both pump limiters and divertors for some present experiments and future large experiments such as INTOR and FED. The neutral gas transport in these experiments was calculated using Monte Carlo techniques. The plasma parameters have been modeled using a two dimensional set of fluid equations. We will discuss recent progress in modeling divertor and limiter designs to maximize the pumping and minimize the impurity evolution.

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*This work supported by U.S. DoE Contract DE-AC02-76-CHO3073

We request a poster session for Tuesday evening, Sessions 2A - 2-B or Wednesday afternoon, Session 3A.

Numerical Studies of the Coalescence of Ion Rings

P. M. Lyster and R. N. Sudan

Laboratory of Plasma Studies, Cornell University, Ithaca, NY 14853

The stabilizing influence of energetic large Larmor radius particles in a field reversed configuration is well recognized.[1] Such a hybrid system[2] can be maintained in the steady state only if it is possible to inject energetic particles that eventually trap within the field reversed configuration. To investigate this feature we have conducted numerical studies employing a magnetostatic, $2\frac{1}{2}$-dimensional (r,z), axisymmetric particle simulation code RINGA.[3] Two self-contained ion rings in a quasi-equilibrium are allowed to merge under mutual magnetic attraction in a resistive background medium. Runs were performed with rings of different field-reversal factor ζ. Results show that the magnitude of the field reversal in the final merged state ζ_F is optimized ($\zeta_I < \zeta_F < 2\zeta_I$) if initially the rings have equal ζ_I and their initial translational kinetic energy is minimized. A large translational energy of the injected ring is not expected to favor coalescence.[4] To investigate this point, runs are being conducted in which pulses of gyrating ions with different axial energies are injected into a stationary field reversed ring. These results will be discussed.

This work supported by U.S. Department of Energy Contract DE-AS02-76ET53065.

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Electron Cyclotron Heating in Weakly Relativistic, Finite-β Plasmas

K. Audenaerde, J. Scharer, N. Lam and J. Beyer

University of Wisconsin
Madison, WI 53706 USA

Electron Cyclotron Heating in Weakly Relativistic, Finite-β Plasmas*, K. AUDENAERDE, J. SCHARER, N. LAM, and J. BEYER, Univ. of Wisconsin -- We examine ECRF wave launching and absorption in the plug and barrier regions of tandem mirrors. The 3-D magnetic field, density and electron temperature profiles are modelled to simulate these regions. It is found that the X mode at elevated temperatures ($T_e \approx 50$ keV) exhibits substantial spatial shifts from the cold plasma resonance surface. For steep plasma density profiles the X-mode bends away from the resonance zone and, furthermore, absorption is concentrated near the plasma surface. The O-mode exhibits a ray trajectory which more easily penetrates to the plasma core and has a moderate absorption at $T_e \sim 50$ keV such that single pass absorption is adequate. The effects of non-Maxwellian loss-cone electron distributions on wave stability and the deposition profile will be discussed. Finally, the use of quasi-optical ECRF launchers to overcome reactor environmental problems associated with standard overmoded waveguide launchers used for gyrotron sources is considered.

*Research supported by DOE contract DE-AC-02-79ET53083 and Research Agreement #130/D2/524350 with Kernforschungszentrum (Karlsruhe).

POSTER SESSION

EFFECTS OF A CONSTANT MAGNETIC FIELD ON COLLISIONS*

Kyoko Matsuda
General Atomic Company
San Diego, California

ABSTRACT

The Rostoker equation[1] (the generalized Balescu-Lenard equation for a magnetized plasma) has been numerically compared with the Fokker-Planck equation for a plasma with axially symmetric velocity distributions by computing test particle slowing down rates and velocity-space diffusion rates. Treatment of ion-clouds surrounding electrons affects even slowing down rates due to electron-electron collisions. If we assume that ion-clouds surrounding electrons are either static or consist of unmagnetized ions, or do not exist, our results for electron-electron collisions in a case of $\Omega_e \lesssim \omega_{pe}$ agree very well with the Fokker-Planck coefficients. In the case of strong magnetic field ($\Omega_e \gg \omega_{pe}$), our results indicate corrections to the Fokker-Planck coefficients which are different from one suggested by Montgomery et al.[2] The effective shielding length for this case could be even larger than the Debye length depending on velocities of test particles.

The electron slowing down rates due to collisions with ions depend on assumptions for ion clouds. The detailed results and also the discussion of ion test particle problems will be presented.

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*Work supported by Department of Energy, Contract DE-AT03-76ET51011

Abstract submitted for poster session
1982 Annual Controlled Fusion Theory Conference

Particle Transport Due To Electrostatic Turbulence in the Caltech Tokamak

P.C. Liewer, S.J. Zweben and R.W. Gould
Department of Applied Physics
California Institute of Technology
Pasadena, California 91125

Large amplitude density and electric field fluctuations in the drift wave range have been measured with probes in the outer regions of the Caltech tokamak. An attempt has also been made to measure directly the particle flux caused by the electrostatic fluctuations, $\Gamma_r = c < \delta n \delta E_\Theta >/B$.[1] Here we review these measurements and compare them with drift wave theory predictions.

The outer regions of the Caltech tokamak, as well as the Macrotor tokamak, are shown to be unstable to the dissipative drift instability. In this region, the collisionality, $\nu_{ei} q\ R\sqrt{T_e/M_e}$, is of order unity and the other parameters, such as shear and gradient scale length, are such that the conditions are satisfied for existence the toroidicity-induced dissipative drift instability.[2] The predicted spectra will be compared to those measured, although the measurements suggest the turbulence is nonlinear. Evidence for the nonlinear nature of the turbulence includes the following: (1) the measured poloidal field fluctuations ($\delta E_\Theta \sim 10$ volts/cm) would cause a perturbed velocity, $\delta V_r = c\ \delta E_\Theta/B$ of the same size as the diamagnetic drift velocity; (2) the level of fluctuations is large, $\delta n/n \sim 50\%$; (3) the spectra remain unchanged over a wide range of operating conditions; (4) the measured correlation lengths are short.

*This work was supported by DOE.

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LOW MODE NUMBER STABILITY OF THE TANDEM MIRROR*

M.W. Phillips and J.D. Callen

Nuclear Engineering Department
University of Wisconsin
Madison, Wisconsin 53706

Low mode number long parallel wavelength modes have been observed in tandem mirror experiments such as Phaedrus and TMX. In an effort to understand these modes we investigate the magnetohydrodynamic stability of low mode number type perturbations in the tandem mirror. A general set of equations governing incompressible magnetohydrodynamic modes in a low beta anisotropic plasma is derived for arbitrary geometry. The full eigenmode equation describing the radial axial variation of the perturbation is solved numerically for a long-thin equilibrium with quadrupole symmetry typical of the tandem mirror. The quadrupole fields cause a weak coupling of azimuthal variation, $\exp(im\theta)$, of the modes and these couplings are treated perturbatively. Specific solutions and stability criteria for the Phaedrus tandem mirror experiment will be given.

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